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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1001

LIGHTNING DISCHARGES TO AIRCRAFT AND
ASSOCIATED METEOROLOGICAL CONDITIONS

By L. P. Harrison
U.S. Weather Bureau

For the Subcommittee on Lightning Hazards to Aircraft



Washington
May 1946

FOREWORD

The following notes are intended to aid the reader of this report in choosing for study those sections most likely to be of interest to him:

(a) Aeronautical engineers will probably be most interested in sections 14, 15, and 23, and appendixes II, III, and IV.

(b) Air-line pilots and operations personnel will be most interested in sections 1 through 11, and in sections 16 and 19 to 22.

(c) Air-line meteorologists will find an additional interest in sections 12, 17, and 18, and appendixes I and III to VII.

For information relative to the protection of gliders and nonmetallic aircraft from lightning, the reader is referred to reference 33.

Attention is invited to new developments in the theory of the mechanism of the thunderstorm given on page 102 (first paragraph) and pages 106 (last paragraph) to 129, of appendix V, following a summary of other well-known phenomena involved in the genesis and maintenance of thunderstorms given on pages 97-101 and 103-106, inclusive.

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1. INTRODUCTION

The Subcommittee on Lightning Hazards to Aircraft of the National Advisory Committee for Aeronautics was created for the purpose of studying all phases of the problem of atmospheric electrical discharges to aircraft and of recommending measures (1) for improving the protection of aircraft against such discharges, (2) for alleviating the hazards to occupants of aircraft from such discharges, and (3) for avoiding conditions under which the discharges may be experienced.

The Subcommittee has been actively engaged in carrying out its functions since the year 1937. The membership of the Subcommittee on Lightning Hazards to Aircraft was as follows in 1941:

Mr. Delbert M. Little, Chairman,
U. S. Weather Bureau,
Washington, D. C.

Dr. O. H. Gish,
Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

Mr. Charles H. Helms,
National Advisory Committee for Aeronautics,
Washington, D. C.

Lieut. Comdr. M. P. Hanson, U.S.N.R.,
Bureau of Aeronautics,
Navy Department,
Washington, D. C.

- Mr. S. Paul Johnston (ex officio),
Coordinator of Research,
National Advisory Committee for Aeronautics,
Washington, D. C.
- Dr. George W. Lewis (ex officio),
Director of Aeronautical Research,
National Advisory Committee for Aeronautics,
Washington, D. C.
- Mr. P. C. Sandretto,¹
Superintendent, Communications Laboratory,
United Air Lines Transport Corporation,
Municipal Airport, Clearing Station,
Chicago, Illinois.
- Dr. Karl B. McEachron,
General Electric Company,
Pittsfield, Massachusetts.
- Dr. Irving R. Metcalf,
Civil Aeronautics Administration,
Washington, D. C.
- Mr. E. J. Minser,
Transcontinental and Western Air, Inc.,
Municipal Airport,
Kansas City, Missouri.
- Lt. Col. Charles K. Moore, Air Corps, U.S.A.,
Materiel Division, Wright Field,
Dayton, Ohio.
- Dr. F. B. Silsbee,
National Bureau of Standards,
Washington, D. C.

¹ In 1942, the commissioning of Mr. Sandretto in the army changed his address and title, which, in 1943, was

Lt. Col. P. C. Sandretto, U.S.A.,
Electronics Unit,
First Proving Ground,
Eglin Field, Florida.

In 1942, the roster of membership of the Subcommittee was modified. Messrs. Helms and Johnston were relieved and the following members were added:

Prof. E. J. Workman,
University of New Mexico,
Albuquerque, New Mexico.

Mr. L. P. Harrison,
U. S. Weather Bureau,
Washington, D. C.

Mr. Russell G. Robinson (ex officio),
National Advisory Committee for Aeronautics,
Washington, D. C.

During 1942, there occurred the lamented death of Lieutenant Commander Hanson. He was replaced, in September 1942, by

Lieut. Comdr. F. G. Kear, U.S.N.R.,
Bureau of Aeronautics,
Navy Department,
Washington, D.C.

Doctor Metcalf was replaced, in July 1942, by

Mr. Joseph C. Hromada,
Technical Development Division,
Civil Aeronautics Administration,
Washington, D. C.

In 1943, Lieutenant Colonel Moore was replaced by

Major E. H. Schwartz, U.S.A.,
Army Air Forces,
Materiel Center,
Wright Field, Dayton, Ohio.

and a new member was added to the Subcommittee:

Dr. Ross Gunn,
Naval Research Laboratory,
Bellevue, D. C.

Numerous investigations on electrical discharges and their effects have been conducted by the members of the Subcommittee, and by organizations whose cooperation was secured to assist in the program of research. A considerable amount

of pertinent data has been amassed under the direction of the Subcommittee and these were made available for study and digest.

This report is a summary of information on atmospheric electrical discharges to aircraft and associated meteorological conditions, prepared for the Subcommittee at the U. S. Weather Bureau, Washington, D. C.

Many of the facts given herein are based largely on data furnished by pilots, meteorologists, and maintenance engineers of the U. S. Navy, the U. S. Army Air Forces, and air-line companies, in questionnaires and other reports prepared in connection with about 170 cases of electrical discharges to aircraft which have occurred during the years 1935-44. Technical data of particular interest to engineers, obtained from the high voltage laboratories of the General Electric Company and the Westinghouse Electric and Manufacturing Company, as well as from other sources, also have been utilized. (See appendix II.)

The following discussion (secs. 2 to 18) outlines the essential facts known about the conditions under which electrical discharges to aircraft have occurred. The discussion, including appendixes III to VII, provides information designed to give a fairly comprehensive view of the underlying principles of meteorology and atmospheric electricity which are involved. A brief glossary of some important meteorological terms is given in appendix I to aid the nonmeteorologist in following the discussion.

Attention of pilots is especially directed to sections 19 to 22, which contain lists of procedures of flight conduct and aircraft maintenance recommended for avoiding or minimizing the hazards of (a) disruptive electrical discharges to aircraft, and (b) other meteorological conditions of severe character often encountered in or near thunderstorms.

Acknowledgments

The Subcommittee on Lightning Hazards to Aircraft of the NACA wishes to express its appreciation for the splendid cooperation rendered by pilots, meteorologists, engineers, and maintenance personnel of many air lines in furnishing invaluable information relating to actual field experiences with electrical discharges to aircraft. Similar appreciation

is due the U. S. Army Air Forces and the U. S. Navy Bureau of Aeronautics for providing data on the subject in relation to service aircraft.

The NACA takes this opportunity to express its gratitude to the airmen and their coworkers who made this report possible by material furnished in questionnaire form, and to the officials and the personnel of the General Electric Company and the Westinghouse Electric and Manufacturing Company who devoted unstinted work in conducting investigations on the nature and effects of lightning discharges for the promotion of greater safety to mankind generally against these hazards of nature. Deep appreciation also is due other organizations and individuals, too numerous to mention, who wholeheartedly contributed their services and advice to the Subcommittee on Lightning Hazards to Aircraft, in pursuit of its activities. Among these may be mentioned: Dr. Harvey Fletcher, Director of Physical Research, Bell Telephone Laboratories, and his assistants; Prof. Clarence H. Graham, of the Psychological Laboratory, Brown University; Prof. J. H. Bryant, Head, Department of Electrical Engineering, University of Minnesota; and Dr. M. B. Visscher, Head, Department of Physiology, University of Minnesota. The NACA is deeply indebted to past and present members of the Subcommittee on Lightning Hazards to Aircraft, who gave so liberally of their time and efforts in carrying forward the work of the organization.

The writer is grateful to all persons and organizations who made available the material which forms the basis for this report. A special debt is due Mr. E. J. Minser, Chief Meteorologist, of Transcontinental and Western Air, Inc., whose writings (references 1 and 2) on the subject have been so helpful as guides in preparing certain portions of the report, especially sections 20 and 21, "Recommended Flight Procedure to Avoid Discharges and Alleviate Harmful Effects," which has incorporated in it a number of the rules and principles which he has suggested for the greater safeguard of air navigation. The pertinent writings of the Meteorology Department of the United Air Lines Transport Corporation, have also been found helpful. (See reference 3.)

The author wishes to express his appreciation to all those whose helpful comments, suggestions, and criticisms have enabled him to make this publication an improvement over his "Preliminary Report on Atmospheric Electrical Discharges to Aircraft," issued August 1941 by the NACA. Among those who may be mentioned in this connection are: Mr. P. Donely, Dr. O. H. Gish, Mr. W. E. Konecny, Mr. Jerome Lederer, Mr. S. Lichtblau, Mr. E. J. Minser, Mr. H. W. Neill, Mr. R. V.

Rhode, Mr. P. C. Sandretto, Dr. F. B. Silsbee, Prof. E. J. Workman, and Dr. A. F. Spilhaus jointly with Prof. G. Emmons. Appreciation is due also to Messrs. A. E. Kussman, R. J. List, and N. C. Gerson of the U. S. Weather Bureau for invaluable assistance in compiling certain of the data on which this report is based.

2. GEOGRAPHIC LOCATIONS AND GENERAL METEOROLOGICAL CONDITIONS

An atmospheric electrical discharge¹ may occur to an aircraft in any locality where the aircraft may encounter or approach closely cloud and precipitation conditions having local regions in which the electrical potential gradient² is sufficiently intense to cause a discharge to be initiated either spontaneously or upon entry of the aircraft into the scene. Such discharges occur with greatest frequency in areas where thunderstorms, or cumulo-nimbus or towering cumulus clouds, develop most often along more or less extensive lines. These developments (along lines) generally take place in connection with the lifting of moist, unstable air by the action of (1) upward sloping or rough terrain, like mountains and coastal slopes, or (2) frontal systems of low pressure areas ("LOWS" or cyclones). Regions where surface heating is intense and the air especially moist and unstable are also breeders of local thunderstorms and convective-type clouds, such as those mentioned, wherein the discharges may be experienced.

¹In this report the terms "atmospheric electrical discharge," "electrical discharge to aircraft," and "discharges" without reference to "corona discharges" in the context are intended to apply to disruptive discharges or lightning. The terms "corona discharge" and "St. Elmo's fire" are used synonymously to apply to glow and brush discharges.

²By the term "potential gradient" is denoted the rate of change of potential per unit distance in the direction of the electric field. It is generally expressed in volts per meter or volts per centimeter. When the potential gradient reaches an intensity which permits sparking to begin, an electrical discharge occurs. The sparking potential gradient is about 1,000,000 volts per meter in a cloud consisting of droplets $1/8$ in. in diameter, or 3,000,000 volts per meter in clear air at sea level, or 2,100,000 volts per meter in clear air at 10,000 ft altitude. The sparking potential gradient for clear air is controlled by the air density; but for cloudy air containing water droplets it seems to be largely controlled by the sizes of the droplets. (See reference 4.)

However, the most severe conditions are likely to be encountered in localities where frontal and /or mountain slope (orographic) lifting acts in conjunction with surface heating on an air mass of moist, unstable character.

The convective-type clouds and the associated precipitation, in connection with which the electrical discharge is experienced, may or may not manifest cloud-to-cloud or cloud-to-ground lightning strokes prior to or after the discharge; hence, true, active thunderstorms are not always involved.

3. ANNUAL VARIATION

True thunderstorms are generally more frequent during the warmer season of the year than in other seasons, but many of the summer thunderstorms are of the local-heat variety and can be circumnavigated. Most of the spring and autumn thunderstorms and convective-type clouds originate primarily from frontal action and orographic lifting. In view of their characteristic of developing along extensive lines, these conditions are more difficult to avoid than isolated, local storms or clouds. Consequently, as shown in the following tables, the records of cases of electrical discharges to aircraft show a pronounced primary maximum frequency of occurrence in early spring and a secondary maximum in autumn. A moderate number occurred in midwinter and in midsummer. (The free-air temperatures, moisture, and instability of the air masses involved, character of precipitation at various levels, and cloud heights in relation to flying levels during the different seasons have important controlling influences on the phenomena which determine the statistics. All the factors mentioned must be taken into consideration in interpreting them.)

Annual variation, by months and seasons, respectively, of the number of cases of disruptive discharges to aircraft according to available data for the period March 1935 through December 1944.

Month	Number of occurrences	Percentage of total
January	6	4
February	7	4
March	22	13
April	29	17
May	20	12
June	27	16
July	4	2
August	9	5
September	14	8
October	13	8
November	13	8
December	5	3
Total	169	100

Season	Number of occurrences	Percentage of total
Winter (Dec. 21- March 20)	22	13
Spring (Mar. 21-June 20)	82	49
Summer (June 21- Sept. 20)	26	15
Autumn (Sept. 21-Dec. 20)	39	23
Total	169	100

4. DIURNAL VARIATION

Disruptive electrical discharges to aircraft have occurred with greatest frequency during the 6-hour interval from noon to 6 p.m. local standard time, which is the period of greatest convective activity near the earth's surface. The frequency of occurrence also has apparently tended to be fairly high during the early evening hours, perhaps as a result of active or incipient thunderstorms which often occur after 6 p.m. in the midwestern, mountain, and some coastal regions of the United States. The minimum frequency has occurred just after sunrise, when convective activity is usually low. In general, the diurnal frequency distribution may be summarized by stating that there is a broad maximum in the first 9 hours after noon and a broad minimum in the first 9 hours after midnight, local standard time. Details regarding the diurnal variation of the phenomenon are shown in the following table:

Diurnal variation, by 3-hour periods, of the number of cases of disruptive discharges to aircraft, according to available data for the period March 1935 through December 1944

Period	Number of occurrences	Percentage of total
12 p.m. - 3 a.m.	6	4
3 a.m. - 6 a.m.	11	7
6 a.m. - 9 a.m.	3	2
9 a.m. - 12 m.	16	10
12 m. - 3 p.m.	35	23
3 p.m. - 6 p.m.	35	23
6 p.m. - 9 p.m.	26	17
9 p.m. - 12 p.m.	15	10
Unknown	6	4
Total	153	100

(In interpreting the statistics it is necessary to make due allowance for the diurnal variation of air transport and the "blind" (instrument) character of night flight through storm conditions, which are superimposed on the results due to the natural diurnal variation of convective and atmospheric electrical activity.)

5. ALTITUDE

Flight altitudes at the time of disruptive discharges to aircraft have varied from 700 to 18,000 feet above sea level. The altitude range wherein the phenomenon has occurred most frequently is from 6000 to 11,000 feet above sea level and 4000 to 9000 feet above ground. The following table shows the actually observed distributions. (Civil Air Regulations require that on-airways flight be conducted at indicated altitudes above sea level corresponding to designated whole thousands of feet. Hence, as shown by the table, the altitudes of maximum recorded frequency of occurrence of discharges to aircraft are coincident with the most frequented levels of on-airway traffic. For this reason the statistics must be treated with reservations.)

Frequency distribution of altitudes above sea level and above ground on the occasion of disruptive discharges to aircraft during the period March 1935 through December 1944 (one case observed July 1922 also included)

Indicated altitude above sea level ¹ (thousands of feet)	Number of cases	Indicated altitude above sea level ¹ (thousands of feet)	Number of cases	Altitude above ground ¹ (thousands of feet)	Number of cases	Altitude above ground ¹ (thousands of feet)	Number of cases
0.0	0	9.5	4	0.0	² 1	9.5	3
.5	² 1	10.0	11	.5	³ 2	10.0	5
1.0	2	10.5	3	1.0	1	10.5	2
1.5	0	11.0	22	1.5	0	11.0	2
2.0	1	11.5	2	2.0	4	11.5	1
2.5	0	12.0	6	2.5	1	12.0	2
3.0	2	12.5	1	3.0	4	12.5	0
3.5	3	13.0	7	3.5	7	13.0	4
4.0	6	13.5	1	4.0	12	13.5	2
4.5	1	14.0	6	4.5	5	14.0	4
5.0	3	14.5	0	5.0	10	14.5	0
5.5	1	15.0	5	5.5	4	15.0	0
6.0	19	15.5	0	6.0	18	15.5	0
6.5	1	16.0	0	6.5	12	16.0	0
7.0	12	16.5	0	7.0	13	16.5	1
7.5	5	17.0	0	7.5	7		
8.0	20	17.5	0	8.0	9		
8.5	1	18.0	2	8.5	3		
9.0	17			9.0	12		

¹The altitudes shown represent the midpoint of the class interval which is 500 ft. For example, the designation 1000 ft represents the range 750 to 1249 ft; similarly, the designation 1500 ft represents the range 1250 to 1749 ft. The indicated altitudes above sea level are based on readings of altimeters usually adjusted to the barometric altimeter setting of the nearest weather station reporting by radio. Altitudes above ground are derived from the former data by subtracting the estimated ground elevations.

²Occurred while aircraft was on the ground.

³One case occurred at 200 ft.

6. TEMPERATURE

A total of 150 reports of disruptive discharges to aircraft with temperature data included were available for this study. Of this total, 88 percent (132 cases), occurred at temperatures of 41° F or lower. The temperatures concurrent with the discharges fell with greatest frequency in the range 28° to 35° F, since 59 percent (88 cases) were concentrated within this interval. The values 28° and 32° F were reported most often (15 and 23 cases, respectively). The average temperature of the 132 cases reported at 41° F or lower was 30.5° F; while the average temperature of the 88 cases between 28° and 35° F was 31.5° F. The lowest temperature involved was -5° F, observed within a thunderstorm at 18,000 feet above sea level. The highest temperature reported was 85° F. This value was observed about the time of a disruptive discharge to an airplane which was located approximately 5000 feet from what was apparently a cumulo-nimbus cloud, the airplane being at an altitude of 3600 feet above ground. The 85° F value of temperature, reported for a location in southwest Arizona during April, appears to be too high and is open to doubt. However, a report is at hand regarding a disruptive discharge to an aircraft in another location at a temperature of 82° F. This occurred 50 feet below a cumulo-nimbus cloud base which was 900 feet above ground.

Statistics regarding the frequency of different temperatures observed at time of occurrence of disruptive discharges to aircraft are given in appendix IV. (The selected flight altitudes and the prevailing meteorological conditions in the various seasons and localities largely determine the free-air temperatures experienced at the time of the disruptive discharges. It is difficult, on the basis of the statistics alone, to separate the effects of the various factors involved and to appraise their relative importance. However, for independent evidence concerning the correlation of temperature with conditions under which high potential gradients will be found, the reader is referred to section 17 and appendix VI.

7. CLOUD AND THUNDERSTORM CONDITIONS

The prevailing sky condition on the occasions of disruptive discharges to aircraft was overcast, although broken clouds were experienced with fair frequency.

The principal cloud types in connection with which the electrical discharges took place were cumulo-nimbus, cumulus, and strato-cumulus, with a few other types occasionally indicated. The cases involving these principal cloud types were roughly in the ratio of 10:5:3, respectively. They are all of convective origin.

A great majority of the disruptive discharges took place while the aircraft were definitely in clouds. A small proportion occurred while the aircraft were flying in and out of, or just emerging from, clouds, in every case quite close to the source. A slightly smaller proportion suffered a lightning discharge while definitely outside of clouds at distances varying from 20 to 5,000 feet.

Of the first-mentioned cases, namely, those definitely in clouds, only 45 percent reported that lightning was observed in the vicinity before or after the discharge, thus showing that active thunderstorm conditions were manifested in slightly less than half of the cases. The reports in the remaining 55 percent indicated that no natural lightning was observed in the vicinity of the aircraft immediately prior to or following the occurrence of the disruptive discharge. From these data and other considerations (see sec. 18) it may be inferred that the presence of the aircraft is instrumental in initiating disruptive discharges in some cloud conditions where lightning would not have developed spontaneously in the absence of the airplane, other factors being equal.¹

The instances where disruptive discharges were experienced outside of a cloud were practically always associated with cumulo-nimbus clouds or active thunderstorms. The cloud was invariably of the cumulo-nimbus or (presumably towering) cumulus type when the discharge to the airplane took place while it was flying in and out of, or just emerging from, the cloud. (There is some doubt about certain of the data since it is difficult to classify clouds in instrument flight under overcast conditions. Thus some cases in middle latitudes wherein cumulus clouds were reported actually must have involved clouds of the cumulo-nimbus type, as evidenced by the presence of showers or hail.)

¹The data lead to the implication that some cumulo-nimbus and perhaps other clouds have potential gradients insufficient for the evolvment of natural lightning, yet sufficient for the formation of a disruptive discharge when altered by the intrusion of an airplane into the scene.

8. PRECIPITATION CONDITIONS

Considering the cases where the discharge was experienced while the aircraft was definitely in a cloud, all of them, with three exceptions, involved concurrent encountering of precipitation in some form. The distribution by kind of precipitation, both in and out of clouds, was as follows: rain alone, 31 percent; rain mixed with some form of frozen precipitation, 23 percent; and some form of frozen precipitation alone, 33 percent. The types and intensities of precipitation encountered are shown in the table below. The statistics show that nearly three-fifths of the cases involved frozen precipitation at the same time, with snow being the predominant form. This result is consistent with the temperature data previously cited.

It is important to note that conditions favorable for an electrical discharge to an aircraft can be encountered in snow and in related forms of precipitation.

Frequency distribution of precipitation types and intensities on the occasions of disruptive discharges to aircraft during the period from March 1935 through December 1944 (This table includes cases both in and out of clouds.)

Precipitation type	Intensity of precipitation			Total No. of cases	Percentage of total
	Light	Moderate	Heavy		
Rain	15	21	14	50	31
Snow	6	14	9	29	18
Ice crystals	0	1	1	2	1
Sleet ¹	1	4	2	7	5
Hail	1	1	2	4	2
Rain and snow	3	13	7	23	14
Rain and sleet ¹	1	1	2	4	2
Rain and hail	1	1	1	3	2
Rain, snow, and sleet ¹	0	3	1	4	2
Rain, snow, and hail	2	1	0	3	2
Rain, snow, sleet ¹ , and hail	0	1	0	1	1
Snow and sleet ¹ or ice pellets ¹	1	6	1	8	5
Snow and hail	0	1	1	2	1
Snow, sleet ¹ , and hail	0	0	1	1	1
No precipitation	-	-	-	18	11
Not reported	-	-	-	4	2
Total	31	68	42	163	100
Percentage of total	19	42	26		

¹It is probable that some of the precipitation reported as sleet was actually small hail. This opinion is based on current meteorological definitions of these hydrometeors.

9. TURBULENCE

Statistics regarding the degrees of turbulence experienced at the times of disruptive discharges to aircraft are given in the following tables. It is instructive to note that there was a slight tendency for stronger (severe or moderate) turbulence when a frozen form of precipitation was encountered than when rain alone was encountered. This tendency was more pronounced when a comparison was made between the degrees of turbulence when frozen forms of precipitation were present and no precipitation was present and still more marked when turbulence involving hail was compared to turbulence involving no precipitation.

In the reports covering the period 1935 through 1940, during which time comparatively small size aircraft were in general use, it was found that when hail or some form of frozen precipitation was encountered the proportion of cases of severe turbulence to cases of moderate and slight turbulence was considerably greater than when rain alone was encountered. However, the reports since that time (1941 through 1944) involved larger planes and indicated a preponderance of slight over moderate and severe turbulence. Owing to the relative basis of pilots' judgment of the degree of turbulence, this recent tendency in the reports may be attributed to the use of larger and heavier planes, improvements in the skill of pilots, improvements in the structure of aircraft, and so forth, all of which generally lead to lower estimates of the intensity of this phenomenon. A more definite summary could be made if there were available an instrument which could accurately determine the various degrees of turbulence.

Frequency distribution of various degrees of turbulence encountered in the principal cloud types, other cloud types, and out of clouds, on the occasions of disruptive discharges to aircraft during the period from March 1935 through December 1944

Cloud condition	Degree of turbulence						Total number of cases
	Slight		Moderate		Severe		
	Number of cases	Percent of cases	Number of cases	Percent of cases	Number of cases	Percent of cases	
Cumulo-nimbus	25	15	22	13	7	4	54
Cumulus	17	10	14	8	2	1	33
Strato-cumulus	12	7	3	2	0	0	15
Nimbo-stratus	2	1	1	1	3	2	6
Other clouds	15	9	13	8	2	1	30
Out of clouds	17	10	6	3	1	1	24
Data incomplete					18	14	8
Total	88	52	59	35	18	14	170

¹Degree of turbulence or cloud condition not reported.

Frequency distribution of various degrees of turbulence according to precipitation conditions on the occasions of disruptive discharges to aircraft during the period from March 1935 through December 1944

Precipitation condition	Degree of turbulence						Total number of cases
	Slight		Moderate		Severe		
	Number of cases	Percent of total	Number of cases	Percent of total	Number of cases	Percent of total	
None	15	9	3	2	2	1	20
Rain	27	16	17	10	5	3	49
Rain and frozen precipitation	15	9	13	7 ² / ₃	1	¹ / ₂ ² / ₃	29
Frozen precipitation	19	11	22	13	4	2	45
Hail	3	2	0	0	2	1	5
Hail and rain	1	² / ₃	1	² / ₃	1	² / ₃	3
Hail and frozen precipitation	1	² / ₃	1	² / ₃	0	0	2
Hail, rain, and frozen precipitation	1	² / ₃	3	2	¹ / ₂ 10	² / ₆ ² / ₃	5
Unknown							10
Total	82	49	60	36	² / ₁₀ 16	² / ₆ 9	168

¹The fraction $\frac{2}{3}$ indicates $\frac{2}{3}$ of 1 percent.

²Degree of turbulence or precipitation condition not reported.

10. CONVECTIVE ACTIVITY IN CUMULIFORM CLOUDS

AS CONTROLLED BY AIR MASS CONDITIONS

As is clear from the data already presented, disruptive discharges to aircraft require for their origination the existence of a cloud and precipitation condition characterized by convective activity favorable for the development of intense electric fields. The presence of a meteorological

setting conducive to the formation of such fields is greatly determined by (a) the characteristics and interactions of the air masses which form the basic constituents of the weather situation, and (b) the physical processes which take place within and between the air masses. (See appendixes I and V for introductory, explanatory material.) Since the air masses are basic elements in the meteorological environment, it is essential to give them first consideration from the standpoint of those properties which control convective activity and cloud formations. From the statistics given in the next section, it is evident that the convective activity and cloud developments which yield conditions favorable for disruptive discharges to aircraft are generally resultants of the interaction of air masses of tropical and polar origin, perhaps conditioned by passage over land or water surfaces, and modified or operated upon by various physical processes.

Tropical maritime air masses which are generally warm, moist, convectively unstable at moderate elevations (about 2500 to 6500 ft or somewhat higher), and often conditionally unstable to or above the level of 15° F temperature, are most favorable for the development of convective-type (cumuliform) clouds and thunderstorms when acted upon by the processes outlined in appendix V. Other moist air masses like those of Polar Pacific origin, which are modified by passage over a warmer surface and thus have become unstable, are also relatively favorable for such consequences. Fresh outbreaks of cold polar or arctic air masses rapidly passing over moist terrain, considerably warmer than themselves, are also conducive to the developments in question, provided the warming from below is sufficiently prolonged to wipe out hindrances to penetrative convection to high levels, such as low-lying inversions. (An "inversion" is an increase of temperature with height.)

If an air mass is absolutely stable while condensation takes place, the clouds produced will form in layers, that is, will be stratiform (as explained in appendix V), and the chances of electrical discharges to aircraft will be relatively slight. But if the air mass is conditionally unstable, the clouds will be of the cumuliform variety, and the chances of experiencing a discharge very much greater.

The important clouds from the standpoint of this study are: cumulo-nimbus, cumulus, and strato-cumulus. The definitions are as follows:

Strato-cumulus: A layer (or patches) composed of globular masses or rolls; the smallest of the regularly arranged elements are fairly large; they are soft and gray with darker parts. These elements are arranged in groups, in lines, or in waves in one or in two directions. Very often the rolls are so close that their edges join together.

Cumulus: Thick clouds with vertical development; the upper surface is dome-shaped and exhibits rounded protuberances while the base is nearly horizontal.

Cumulo-nimbus: Heavy masses of cloud, with great vertical development, the cumuliform summits of which rise in the form of mountains or towers, the upper parts having a fibrous texture and often spreading out in the shape of an anvil. (The fibrous texture is indicative of the presence of ice crystals.) Cumulo-nimbus clouds generally produce showers of rain or snow and sometimes of hail, and often thunderstorms as well.

Cumulo-nimbus clouds generate the heaviest quantities of electrical charge and contain the most intense electrical fields. They also are most hazardous on account of the great strength of turbulent currents and more frequent presence of hail.

Cumulo-nimbus clouds generally develop by transformation from a towering cumulus cloud after the top of the cumulus cloud has grown by convection up to a level where freezing of water-cloud particles occurs. The presence of ice crystals formed by this freezing has an important bearing on the characteristics of cumulo-nimbus clouds mentioned.

Each active towering cumulus and cumulo-nimbus cloud has a more-or-less vertical core of rapidly ascending moisture-laden air. It usually is displaced somewhat toward the leading half of the cloud. Surrounding this core is a zone of air extending to the edge of the cloud, which is characterized by descending currents a good portion of the time. Many exceptions to this distribution may be found due to local irregularities, but in every case turbulence is likely to be severe where strong conflicting currents adjoin. This is also true to some extent in the general neighborhood of the freezing level in active cumulo-nimbus clouds. The vertical, upward velocity of the core ranges from rates of about 1000 feet per minute or slightly higher in ordinary, middle latitude, moderate cumulus clouds to as much as 9000 feet per minute or more in thunderstorms where large hailstones form.

The top of the rising current is usually very turbulent in active, growing clouds. The downward velocities are roughly of the order of one-half of the upward velocities but at lower levels greater values can sometimes be expected.

The ascent of the core of air is due to prevailing instability of the atmosphere under saturated conditions, which gives rise to convection. The greater the degree of instability the more vigorous will be the convection and the more rapid will be the rate of feeding of water vapor into the cloud system. In addition, the larger the vapor content of the air mass, the lower will be the cloud base and the more copious will be the supply of vapor and of latent heat for maintaining convection after condensation begins. When the air mass is convectively unstable, the smaller the amount of lifting necessary to secure release of the instability, the greater is the likelihood that the energy inherent in the stratification will become available for convective activity in the clouds. The deeper the layer characterized by instability (for unsaturated air below the cloud and for saturated air within the cloud layer), the greater will be the height to which the clouds grow and the more intense will be the convection. To assure cumulo-nimbus and thunderstorm formation, it is essential that the instability for saturated air extend to elevations appreciably above the freezing level. The farther above this level the region of conditional instability extends, the more probable will be a transformation from cumulo-nimbus cloud to active thunderstorm, and the heavier will be the showers emanating from the storm. In those cases where the freezing level in the cloud is a considerable distance above the lowest level at which free thermal convection begins, and where the convective energy imparted to parcels ascending through the interval is relatively great, the velocity of the rising saturated currents becomes quite large within the freezing zone. The cloud can then readily build up to heights well above the freezing level. Moreover, considerable quantities of water can be entrained in the strong updrafts, so that the concentration of ice crystals and water particles becomes great. The ice crystals grow by condensation of vapor and by collisions with supercooled water particles which freeze on contact at temperatures below 32° F. Sleet pellets and snow crystals thus are produced. When sufficiently heavy they fall, colliding with other particles and grow further. On falling below the freezing level they melt,¹ thereby forming large raindrops. Hail also may form if the sleet pellets suffer several up and down transits in the turbulent, wet air. When the updrafts are cut off in any way or are so reduced in strength as to have less velocity than the velocity of fall of the particles in still air, the water, hail,

¹Provided the potential pseudo-wet-bulb temperature exceeds 32° F.

and so forth, held in suspension descend in torrents. Evaporative cooling below, aided by other thermodynamic processes, may augment the instability and cause accelerated descent of considerable quantities of underlying air. Downdrafts then become extremely powerful, and usually dangerous. Aircraft caught in such strong descending currents might possibly be carried to earth. Twisting eddies with high accelerations may become so overwhelmingly violent in the boundary region between the updrafts and downdrafts of thunderstorms and well-developed cumulo-nimbus clouds that aircraft can become unmaneuverable or suffer damage. In addition, heavy ice may be deposited on an aircraft in the supercooled water portion of the cloud.

High concentrations of electric charges are built up in particular regions of the cumulo-nimbus cloud by the action of certain electro-generative processes to be discussed later. (See section 17, and appendix VI.)

Accordingly, the phenomena described in the preceding few paragraphs are highly conducive to the development of cumulo-nimbus clouds and thunderstorms in which conditions very hazardous to aircraft may be encountered.

The adverse conditions in towering cumulus clouds may approach in intensity those outlined above for cumulo-nimbus clouds and thunderstorms.

Tropical cumulus clouds usually are characterized by especially severe turbulence and should be avoided. This injunction affects nighttime flying in the tropics.

11. STATISTICS ON GENERAL METEOROLOGICAL SITUATION

The classification of appendix V regarding meteorological processes involved in the development of cumuliform clouds is helpful in analyzing the general meteorological situations prevalent on the occasions of atmospheric electrical discharges to aircraft. Restricting the statistics to the period 1938-44, inclusive, the following table shows the number of cases of such discharges to aircraft in clouds and precipitation classified according to processes involved in their development. Owing to the great multiplicity of meteorological factors operating in some instances and to the difficulties of making correct analyses of synoptic weather charts in complex situations, some of the cases

reported in certain categories hereunder may not be properly classified. However, it may be expected that the data do indicate nearly the proper proportions at least in the predominant and simple categories.

Number of cases	Causative processes of clouds and precipitation involved (according to reports rendered by air-line meteorologists)
39	Cold-front action (alone)
17	Warm-front action
16	Heating of an air mass from below
15	Orographic lifting intensifying frontal action (1 case occluded front; 14 cases, cold front)
14	Orographic lifting (alone)
11	Occluded and upper-cold-front action ¹
8	Prefrontal action
7	Convergence ² (alone)
5	Combination of orographic lifting, convergence, and frontal action
5	Combination of orographic lifting, convergence, and heating of air mass at surface
4	Orographic lifting plus convection from heating of air mass at surface
2	Wave action in conjunction with an occluded front
2	Lifting at an intertropical front

¹A diagrammatic representation of upper-cold-front action may be found in fig. 63, p. 90, reference 5.

²Convergence.—Air-line and army meteorologists who furnished the outline for this breakdown attributed these cases to convergence alone. It is probable that other concomitant causes were also involved, and that with more definite information these cases could be distributed among the other categories.

Although the data imply the indicated processes are the principal causative factors, it must be recalled that a number of factors usually operate in sequence or concurrently, either paving the way for the final event in question or immediately bringing it about. The information conveyed by the table must be viewed with this reservation in mind.

The table indicates that in the cases under consideration, cold-front action was by far the predominant causative factor leading to the cloud formations and precipitation involved in disruptive discharges to aircraft. Also of considerable importance were the effects due to warm-front action, heating of an air mass from below, orographic lifting (operating alone or in conjunction with cold-front action) and occluded- and upper-cold-front action.

Probably the reason these factors appear most frequently is that cumuliform clouds and thunderstorms produced by all types of frontal action and orographic lifting develop along lines which are difficult to circumnavigate, whereas those produced by heating at the surface develop more or less in isolated groups which are comparatively easy to avoid and hence are not so often reported.

12. ST. ELMO'S FIRE (CORONA) AND PRECIPITATION STATIC

As a rule, but not invariably, disruptive electrical discharges to aircraft flying in clouds or precipitation have been preceded by moderate or severe St. Elmo's fire or precipitation static. The proportions with which the different intensities have been experienced under these circumstances are shown by the following data: slight, 16 cases; moderate, 45 cases; and severe, 79 cases.

The time prior to the disruptive electrical discharge that the static or St. Elmo's fire was first noticed varied from $4\frac{1}{2}$ hours to a fraction of a second. The most frequent time was in the neighborhood of 2 to 3 minutes, although 20 to 30 seconds was also quite frequent.

Some idea of the relative distribution of St. Elmo's fire on the various parts of the airplane is given by the following data which represent the number of times the phenomenon was reported at the indicated locations: propeller, 41; nose, 22; wing, 18; windshield, 8; static and pitot tubes, 4; windshield wiper, engines, transmitter, and entire airplane, each 1. It is probable that corona discharges and streamers often have occurred at tail and other surfaces but were not reported because the pilot did not see them.

The St. Elmo's fire took a form varying from fine-brush discharges to corona streamers ranging approximately from a few inches to 10 to 15 feet, or even longer (the latter roughly 4 to 6 in. wide), streaking from the propellers and

projecting forward like forked fingers from the wing tips. A halo of the streamers might envelop the engine or the nose of the airplane.

Theoretical Discussion

The corona discharges, being visible only as St. Elmo's fire in the darkness and invisible in the daylight, could not always be observed, even though present. Precipitation static, which consists of "crying," hissing, or "frying" noises that may run up and down the musical scale in the radio receiving set, is apparently due to corona discharges from various sharp or convex points on the aircraft. The corona discharge takes place only from a given point when the potential gradient in the air adjacent to the point reaches a certain critical value, depending largely on the air density. The discharge has the character of a direct current with steep wave-front current impulses which produce radio interference and seriously hamper the usefulness of radio equipment. (See references 6, 7, and 8.)

Metallic aircraft, while flying through certain meteorological conditions, can build up potential gradients of considerable magnitude at favorable points, principally by the following processes:

- (a) Generation of electrical charges by triboelectric effects (that is, by friction or contact), involving the action of the moving airplane and its parts (including propellers) on solid, especially dry, suspended particles, such as ice crystals, snowflakes, sleet, hail, sand, and dust encountered in flight. The action may be by splitting, glancing collision, or pressure, that is, piezoelectric effects. The mechanism of charge generation involving solid particles is by far the most effective of all the mechanisms here listed (a-d). Wet snowflakes, by themselves, give little electrical charge to an aircraft encountering them.
- (b) Generation of electrical charges by triboelectric effects involving the action of the moving airplane and its parts on suspended water droplets encountered in flight. Generally, the violent disruption of the droplets (by accelerations or decelerations of the medium carrying them, as

shown by Lenard (see reference 9)) causes the larger fragments to acquire positive electrical charges and the more minute fragments flung off or the associated ions carried by the air to acquire negative charges. The residual, larger fragments, coming into contact with the aircraft, impart their charges to it. Compared to the mechanism given under (a), the Lenard effect is of relatively little importance from the present viewpoint and charges the airplane to a minor degree.

- (c) Collection of electrical charges on an airplane by collision with predominantly positively or negatively charged cloud or precipitation or dust particles, or ions. (This phenomenon is likely to be of minor importance under ordinary circumstances.)
- (d) Generation of electrical charges by a mechanism involving, first, induction of charges of some given sign on leading and trailing edges, respectively, of wings, due to the influence of the electrical field component which coincides with the heading of the airplane, and second, selective attraction to the leading edge of charged particles having opposite sign. (This induction process is analogous to that described by Wilson for electrification of falling drops in a vertical electrical field. (See appendix VI.) It is possible that the process for present purposes is not likely to yield important quantities of electrical charge.)

The foregoing processes will be most effective for charging up the airplane when they act cooperatively. It is apparent that this cannot occur except in precipitation and in clouds which tend to generate electrical charges within themselves and which are acted on by mechanisms that permit separation of the opposite charges, thus leading to creation of strong electric fields. Therefore, cumulus and cumulonimbus clouds as well as thunderstorms come into consideration here. In addition, precipitation from such clouds generally carries charges; while snow and ice crystals likewise do when in turbulent air because of triboelectric effects among the particles themselves. Fogs and stratiform clouds consisting of water droplets are not characterized by strong electric fields and usually are not associated with St. Elmo's fire and static. Dust storms generally lead to generation of

electrical charges by triboelectric action and marked modification of the earth's electric field, so that corona discharges are possible therein.

During flight through falling snow and ice crystals, especially when cold and dry conditions prevailed, pilots have often experienced corona discharges. Airplane windshield have thus been observed to glow with a brush discharge. This probably is due largely to the fact that triboelectric action involving frozen moisture particles is highly efficacious for producing charges, doubtless more so than for liquid water, weight for weight. An additional fact, based on observations by pilots is that the transition stage in which water droplets are forming by melting of snow is likely to be characterized by especially intense corona discharges and precipitation static. Light rain ordinarily yields little or no static.

The explanation of the causes of corona discharges during flight is not simple, and all the details are not fully known. However, it appears reasonable to consider that the following two factors are of primary importance in connection with the phenomenon:

1. Under circumstances favorable for the operation of the electrical generating and collecting processes outlined, the airplane will acquire electrical charges. When the charges are acquired, they distribute themselves over the entire external conducting shell of the airplane. However, in view of the mutual repulsion of like charges they tend to concentrate in the extremities, especially on parts of greatest convexity like wing tips, tail, nose, propeller tips, non-shielded radio antennas, or any other existing sharp points or edges. Owing to this effect, the potential gradient in the immediate neighborhood of the airplane, due to the concentration of charges, will be a maximum in the air space adjacent to the projections of greatest convexity. When the amount of accumulated charge is sufficient, the resulting potential gradient in the air adjacent to the more sharply curved projections may exceed the critical potential gradient at which the air ceases to be a good insulator and breaks down electrically. Then, brush or corona discharges occur from the protuberances in question. A greater accumulation of charges will lead to development of the critical potential gradient near blunter projections and so extend the corona discharges to additional parts of the airplane.

2. When the airplane is in an electric field, say between two oppositely charged regions within a cloud, negative charges are induced on that portion of the airplane's conducting surface which is on the side of the positively charged cloud region, while equal positive charges are induced on the opposite surface. This effect is independent of any net charge which the airplane may have acquired. The concentration of induced charges is greatest at protuberances or points of greatest convexity in line with the original field and the resulting potential gradient is most intense in the adjacent air spaces.

The phenomenon may be summarized by saying that the mere presence of the metallic craft will distort the electric field in its neighborhood in such a way that the potential gradient at those extremities of the aircraft which are directed parallel to the field will be many times as great as the potential gradient of the undisturbed electric field prior to entrance of the airplane on the scene. This may be illustrated by the following hypothetical example: if an uncharged (all-metal) airplane had the shape of a sphere, its introduction into a uniform electric field would distort the field and produce a maximum of potential gradient in the air spaces adjoining diametrically opposite points on the sphere lying in the direction of the original field. The potential gradient at those points will be three times as great as the original potential gradient in the undisturbed field. The potential gradient at sharp protruding objects in the neighborhood of these points would be very much greater because of the concentration of charges mentioned.

When the initial potential gradient of the field is sufficiently great, the process of induction of charges just outlined may intensify the potential gradient to such an extent near favorably situated protuberances that the critical potential gradient at which coronas form will be attained. As previously explained, this leads to St. Elmo's fire at these projections and radio interference.

A disruptive discharge does not follow unless the average potential gradient in the space between airplane and charged cloud regions is sufficiently high to permit the propagation of pilot streamers from the airplane to these regions, so that the charges may be tapped and a lightning discharge ensue. (See appendix VII and section 18.)

It is possible for the two factors described ((1) acquisition of charges, and (2) intensification of potential gradient

at extremities due to distortion of field by induced charges) to act cooperatively, thereby strengthening the potential gradient to a greater degree than is possible by the action of either factor alone. In this manner coronas of considerable intensity may be produced.

On comparing the relative potentialities of the two factors in question, it seems likely, and there are reasons for believing, that the more intense glow and brush discharges may be experienced when approaching the edge of a charged cloud, or when flying in a strong electric field between two oppositely charged regions of cloud. Corona discharges are generally milder if due only to the acquiring of a net charge by the airplane. Discharges from this cause will be encountered more frequently than those from strong electric fields, especially when flight is conducted where ice crystals are plentiful or where dust storms are in progress.

Static interference in the radio equipment may become very severe from the marked steep wave-front current impulses which characterize corona discharges of notable degree. An intensification of the disturbance also may occur by the impact of electrically charged precipitation particles upon exposed antennas or other radio parts which shock-excites the radio circuit and creates interference.¹

Pilots have reported, in accordance with theory,¹ that increase in intensity of the corona discharge, judging by visual observations, is attended by increase in severity of the radio interference.

Various devices have been used to reduce precipitation static. (See, for example, references 6, 7, and 8.) With regard to these, Gunn¹ has summarized the matter as follows:

- (a) Shielding of the receiving antenna loop has been observed to reduce interference under all conditions at low frequencies.
- (b) Discharge devices connected to the airplane notably reduce the interference, especially at temperatures below 20° F, if they are placed at a considerable distance from the airplane, by use of a trailing wire or otherwise electrically decoupled from the airplane.

¹Gunn, Ross (U.S. Naval Research Laboratory): Information as reported at a National Defense Research Committee conference.

- (c) The quasi-musical nature of much of the interference and the fact that maximum reduction is obtained when the sharp points are removed a few feet from the airplane emphasizes the fact that a large percentage of the actual interference is local in nature.

Effects of Speed

It has been reported often that the intensity of precipitation static increases with increase in airplane speed, and that the intensity of the static may be reduced by decreasing the speed.

Several explanations have been offered for this phenomenon. In regard to these it should be noted that the larger, faster, and more numerous the propellers, and the larger and faster the airplane, the more rapid is the rate at which it may produce and acquire charges. When just enough charges are accumulated at lower speeds to cause attainment of the sparking potential gradient near projections of greatest convexity, a limited amount of corona discharges must result. This involves an equilibrium condition wherein the rate of leakage of charges from the airplane via the corona currents is equal to the relatively low rate of accumulation of charges. As the speed, and hence the rate of accumulation of charges, is increased, there is an augmentation of the charges held on the airplane, attended by an increase in its potential. This follows because the limited leakage of charges from the sharper points has been insufficient to prevent this change in potential from occurring. Therefore, the potential gradient will be intensified at these points and the sparking potential gradient may be attained at projections of less and less convexity. Consequently, the total corona current, and hence the intensity of the precipitation static, must increase with the speed and the other factors noted.

Further explanation of the relation between speed, corona discharges, and precipitation static may be found in the effects of an airplane flying through charged precipitation or cloud particles. The motion of the airplane relative to the particles forces them to be driven closer together and then possibly to coalesce. If two liquid water droplets possessing an equal quantity of like charges are caused to merge, the resulting single, larger droplet will have a greater field strength at its surface than the original droplets, barring changes in the external field conditions.

Differences of potential are thus established between large droplets and smaller droplets similar to those from which they are formed by coalescence. (This may be readily shown to be the case under the assumption that equal like charges reside at the surface of the smaller droplets and that the droplets behave like conductors.)

When the larger droplets are brought into juxtaposition with the remaining smaller droplets, a corona discharge or spark may form between them because of the potential differences in question. If this occurs as the droplets become contiguous to the airplane, the corona or spark will convey charges to or from the metallic structure. If the latter is at a different potential than the droplets, the sparking will be heightened. Thus, as the intermingling large and small droplets are swept along the surface of the aircraft, the multitude of minute currents produced irregularly in this fashion creates radio interference. As the speed increases, the effect will undergo a corresponding intensification.

An attendant phenomenon is of interest here in connection with the ram action of the airplane. The driving of the airplane through visible moisture crowds together a myriad of the precipitation or cloud particles. If these are largely of one sign electrically, the squeezing or concentration of any given number of the charged particles into a smaller space increases the local field intensity and potential gradient. As a consequence, there is greater electrical induction on the surface of the airplane structure and hence strengthening of the potential gradient near the extremities. Since increased speed produces greater ram action, it follows that this will be accompanied by greater manifestations of corona and precipitation static.

Another effect of coalescence of water droplets now may be indicated. Macky (reference 4) has shown experimentally that larger droplets will go into corona at a lower potential gradient than smaller droplets. Before the passage of the airplane the existing field might have a potential gradient just insufficient to cause the original small droplets to go into corona, but when larger droplets are formed by the action of the airplane, the potential gradient may be sufficient to cause corona glow or possibly even sparking at the droplet surfaces. The extent of this phenomenon would be determined by the speed of the airplane, and hence it follows that radio interference would increase with speed, where the corona or sparking from droplets occurs near the surface of the airplane as they impinge.

13. PATH OF DISCHARGE THROUGH AIRPLANES

A concept of the relative frequency with which atmospheric electrical discharges have taken different paths through metal airplanes is given by the following table based on approximate data. (Some of the available reports are incomplete in exact details; so the results are subject to revision.)

Approximate number of cases	Path of discharge or reverse
19	Wing tip to wing tip (or aileron) ¹
7	Wing tip to tail ²
6	Wing tip to trailing antenna or wire
2	Wing tip to fuselage
18	Nose to tail ^{1 2}
10	Nose to wing tip
8	Nose to trailing antenna or wire
2	Nose to fuselage
9	Propeller to tail ²
6	Propeller to wing (or aileron)
4	Propeller to trailing antenna or wire
4	Fuselage ³ to tail ²
5	Fuselage to trailing antenna or wire
1	Pitot-static tube to tail ³
1	Pitot-static tube to trailing antenna or wire
1	Motor to trailing antenna
1	Motor to tail
1	Leading edge at center of right aileron to trailing edge
2	Radio antenna to wing

¹Two cases are not included in the above list since they appear to be due to two or more discharges. In the first case, it was reported that fused marks appeared on both wing tips, the nose, and the tail. Arc-welded spots on the tail cone were blown open, and the trailing antenna was burned off. In the second case, it was reported that lightning burned a small hole in the right wing, and produced pot marks on the propeller blades and the hub. Also, the fixed antenna was burned off the fuselage at the rudder post, and the pickup arm track was burned and buckled.

²Tail — some part of tail assembly, as tail cone, rudder, stabilizer, elevator, tail light, etc.

³Two of the cases listed under "fuselage" here involved the fixed antenna on top of the fuselage.

The foregoing information indicates a preference for discharging via the longest dimension of the airplane, that is, from nose to tail or trailing wire, or from wing tip to wing tip. However, discharges involving much shorter paths and points of entry or emergence on or near the fuselage are not infrequent.

14. STATUS OF TRAILING ANTENNA AND STATIC DISCHARGE WIRE

Only a small proportion of the aircraft which made a report on disruptive discharges were equipped with trailing antennas. In regard to those which were thus equipped, the trailing antenna was reeled out on approximately half of the occasions of disruptive discharge. However, only about one in three of the trailing antennas reeled out was grounded to the aircraft at the time of the discharge. Damage to the radio equipment is quite common when trailing antennas are employed, since existing lightning arresters do not provide the necessary safeguards to the communication facilities in all cases where the antennas are ungrounded.

During the period 1941-1944 there were 83 cases where report was made concerning the use of a static discharge wire; in 45 percent of these (37 cases) the anti-static wire was operative at the time of the disruptive discharge. It is to be expected for reasons outlined later that the ratio of number of cases of damage to radio equipment to number of cases trailing antennas were used is significantly greater than the ratio of number of cases of damage to radio equipment to number of cases static discharge wire is used without trailing antenna. This seems to be borne out by the meager statistics available.

Some adverse and favorable effects of these devices on disruptive discharges are now considered. As previously explained, keeping a trailing antenna ungrounded augments the chances of damage to the radio equipment by such electrical manifestations. However, a grounded antenna may possibly be conducive to a slightly more intense discharge than an ungrounded one, since greater potential differences and more extensive concentrations of electrical charges in clouds may become involved in the former case than in the latter. Any grounded trailing wire provides a cone of protection to the tail, fuselage, and, to a slight extent, the wings, against lightning strokes from certain directions relative to the airplane; however, the wire is burned off at some point if it is struck.

Trailing antennas and wires increase the conductive length of the aircraft and provide sharp-pointed extremities, thereby increasing the chances of a disruptive discharge to the aircraft. For, when an aircraft with a trailing antenna or wire enters a region of steep electrical potential gradient, the increase in length and the presence of the sharp-pointed extremities may be instrumental in setting off a disruptive discharge which might not have occurred in the absence of these modifying factors. (See section 18 for further explanation.) It also appears probable that the intensity of the resultant discharge generally would be greater when a trailing antenna or wire is employed than otherwise.

A favorable aspect is of interest: Grounded trailing antennas and static discharge wires may have some mitigative influence on the frequency of disruptive discharges to aircraft. Thus, the trailing conductors cause leakage of electrical charges from the aircraft, thereby maintaining them at lower potentials and reducing the intensity of corona discharges. Under some circumstances, these effects cause the extremities of the slightly charged aircraft to be subjected to less steep potential gradients than highly charged aircraft of the same geometry, and hence tend to reduce the likelihood of local development of gradients in excess of the value at which sparking begins.

It is probable that the adverse influences of trailing wires are predominant within or near convective-type clouds (such as cumulo-nimbus) characterized by steep potential gradients; whereas the favorable influences are predominant in precipitation of solid form such as ice crystals, dry snow, dust, or sand, where potential gradients are generally weaker than in thunderstorms.

15. LOCATION AND EXTENT OF BURN MARKS OR DAMAGE

The frequency with which various parts of airplanes have sustained damage due to disruptive discharges is indicated in the following table:

Frequency distribution of various parts of the airplane that have been damaged on the occasions of disruptive discharges to aircraft, according to available data for the period March 1935 through December 1944.

Part of airplane	Number of times damaged	Illustrative case number ¹
Wing and/or ailerons ²	81	1,2,9,12,17,18
Tail Assembly ³	57	3,4,5,6,7,8,13,15,18
Trailing wire or antenna	50	3,7,8,10,11,13,16,17
Radio ⁴	32	7,8,9,11,15,17
Propeller	30	1,6,8,9,12
Nose ⁵	29	5,7,12,13
Antenna (fixed)	28	9,11,12
Fuselage (excluding nose)	27	4,10,11,14,16
Fair-lead or auxiliary trailing antenna release	14	13,15,16
Compass	5	5,9
Antenna reel mechanism	3	
Direction finder ⁶	3	
Radio compass	2	
Bulkhead	2	8,15
Fillet (rear of left wing fillet)	1	
Engine	1	10
Lightning arrester	1	8
Cable duct and cable	1	10
Interior lights ⁷	1	
Tail wheel	1	
Pickup arm	1	9

¹See corresponding case number in following text.

²In this classification, each instance where both wings were struck was counted as one case.

³Tail assembly was considered to be any part or group of parts among the following: elevator, rudder including tubular rudder bow, stabilizer, tail cone, static cartridge tube, and tail light.

⁴Includes three cases where the radio became temporarily inoperative.

⁵Cases classified as "nose" include a few cases of damage to pitot-static tube.

⁶Includes one case where the direction finder became temporarily inoperative.

⁷Trouble light in pilot's cockpit and dome light in navigator's compartment burned out; no fuses burned out, however.

The statistics reveal, as would be expected, that damage occurs most often to the extremities of the aircraft, with some preference shown for parts of small radius of curvature or sharp edges, such as of wing tips, ailerons, rudders, trailing wires, and so forth. However, it should not be inferred from this statement that exposed parts of large radius of curvature are immune from damage due to lightning strokes, since the fuselage has suffered such damage on numerous occasions, and a fillet (between wing and fuselage) was subjected to lightning burns in one case.

Illustrations of the more severe cases of damage are shown in figures 1 to 13.

The damage to the aircraft may consist of: burning off of the fixed or trailing antenna or trailing wire; fusion of fair-lead; fusion of parts in radio circuits; small holes burned in or through tubular rudder bow, stabilizer former, or elevator frame and adjacent fabric scorched, burned, or torn loose; small pit marks or fused spots burned on skin, rivets, and so forth; small holes burned through skin or de-icing shoes; small holes burned through bulkhead; pit marks burned on propeller blades or hub cap; seams opened near tail cone; demagnetization or disturbance of magnetic compass (see cases 5 and 9); automatic direction finder loop motor burnt out; and so forth. Fires were caused inside of the airplane in several cases (see cases 9 and 11), while in other instances smoke alone was observed.

In case 9, two engines cut out occasionally for a few minutes after the discharge. In a second case, an engine appeared to stop for a few seconds, but quickly resumed normal functioning. In a third case, one engine was reported as "rough" for about 45 seconds after the discharge. In a fourth instance (a port engine on a British passenger aircraft struck April 17, 1926), an engine appeared to stop for a few seconds. It continued to miss, at first badly, then to a decreased extent for the next hour. (In the latter case, the compass became completely unreliable. This apparently was due largely to magnetization of nearby engine and radiator control rods and tail adjustment control chain. The permanent magnets of the magneto may have been similarly influenced, and so may have caused misfiring of engine.)

The fused spots referred to give the precise appearance of spot welding with an indentation of the order of one-half the thickness of the skin and an area varying from the size of pinheads to roughly the size of a silver dollar. Where holes

are burned through, beads may be left where the metal melted.

The foregoing statements are illustrated by the following descriptions of damage done in several cases, selected to show the range and nature of damage:

Case 1: Bad burn on one propeller and seven holes of $1/4$ to $1/2$ inch diameter on left wing tip.

Case 2: 37 holes in left de-icer, 27 holes in right de-icer. Holes about as large as pinheads.

Case 3: Trailing wire burned off. Insulation stripped from antenna in tail section.

Case 4: Point of entry: top of rudder. Point of emergence: belly of fuselage. Damage: hole $7/8$ by $3/4$ inch of irregular shape burned on top tubular bow of rudder 10 inches from leading edge. Hole $2\frac{1}{2}$ by $1/2$ to 1 inch wide, of irregular shape burned in side of rudder below hole described above. This hole was in metal leading edge fairing on cap of rudder. Fabric on top of rudder scorched and burned. A hole $1/4$ inch in diameter burned in trailing edge of rudder flettner. Belly of airplane from leading edge of wing to rear compartment rockmarked by small welded spots, with one hole $1/16$ inch diameter burned in under side of wing.

Case 5: Point of entry: airspeed pitot tube. Point of emergence: tubular bow forming top of rudder. Damage: pitot tube head badly burned; pitot heater wiring burned and shorted. Compass demagnetized. Tubular bow forming top of rudder burned almost completely through. First rudder rib from top damaged by secondary discharge. Fabric damaged at both burns. Steel structure in nose section magnetized so that new compass could not be compensated with compensating magnets. Magnetization of steel structure disappeared in approximately three weeks.

Case 6: Point of entry: propeller tip of left engine. Point of emergence: left elevator. Damage: propeller tip burned. Pitted hole approximately $1/4$ by $3/8$ inch burned in left elevator. Propeller burns started at tip and extended in about 10 inches; burns at trailing edge burned to a depth of approximately $1/16$ inch.

Case 7: Point of entry: nose. Point of emergence: trailing antenna. Damage: burned-off trailing wire antenna; burned lead from tuning unit to tail-cone insulator; fused gate latch; many (50 to 60) small fused spots near nose.

Case 8: Point of entry: tip of one blade of left engine propeller (hydromatic). Point of emergence: tail cone of fuselage, radio trailing aerial. Damage: propeller tip slightly fused and plating burned. Rear bulkhead of fuselage, hole 1/4 inch diameter and directly in line another 1/4 inch hole in stiffener of tail cone. Trailing aerial burned off completely, leaving connecting lug and short (1/8-in.) piece of burned wire. Lightning arrester almost completely burned off. Rear bulkhead lead-in Bakelite bushing destroyed. Hole pierced in lead-in Bakelite insulating bracket (transmitting end). Receiver section of Transmit-Receive relay in transmitter completely burned off. Communication receiver rendered inoperative. Two (5-ampere) 12-volt power supply fuses burned out. Transmitter "on" indicator lamp burned out. Transmitter was operative upon using auxiliary trailing aerial. Main range and auxiliary receiver equipment evidently was unharmed, including loop, loop antenna, and two "T" aeriels under airplane.

Case 9: (090444) Apparently two or more strokes were involved in this case since damage to the exterior structure consisted of: a small hole 1/4 inch in diameter burned in the right wing near the leading edge at a point about 3 to 4 feet from the fuselage and 8 inches in front of the right wing fuel tank; pit and scorch marks burned on the propeller blades and hub; top antenna at tip of vertical fin burned through; pickup arm warped; and track on the pickup arm burned and buckled. (The pickup arm was the lowest and rearmost metal part of the aircraft.) The radio equipment and antenna were damaged to the following extent: transmitter-receiver relay and band change switch burned out; receiver switches on instrument panel burned; antenna burned off from fuselage and rudder post; antenna lead-in leaky; master fuse developed 1 ohm resistance; and ground wire on receiver cable burned off. (The antenna extended from wing tip to rudder post to wing tip, with a lead-in from near the rudder post to the center of the fuselage.) The following members were magnetized (polarity not indicated): fuselage structure, landing gear oleos, tail fork, stabilizer structure and struts, steel wing structure, and engine mount fittings. The magnetic compass was useless and indicated 270° regardless of the airplane heading. (Undoubtedly the widespread magnetization of the various structures caused a magnetic field of such intensity in the neighborhood of the compass that the compass indications were determined solely by this permanent but purely local field.)

Case 10: (Short Bros. S.30 flying boat). The aircraft had a trailing aerial 200 feet long. This fused at the point of attachment to the winch which is situated on portside of the hull. At a point where the aerial is close to the skin, the flash struck across to the skin, melting hole 2.8 inches square in a cable duct, split 2 Z-section stiffeners, split the skin, and burned a fabric-constructed heater duct apart. The cables in the duct suffered slight damage. A slight fire was caused in the cockpit but was extinguished in 40 seconds. Two engines cut out occasionally for a few minutes afterward.

Case 11: (041444) Point of entry: right rear fuselage. Point of discharge: trailing antenna. Examination of the airplane showed 10 small holes burned on the right rear fuselage. The command antenna was burned off with the exception of approximately 2 feet at each terminal. Approximately 150 feet of trailing antenna which was unreel at the time of discharge was burned off. One wire leading into the liaison transmitter was burned brittle and the liaison transmitter relay burned. (The 10 marks on the fuselage may represent the terminal of 1 stroke which had 10 successive current peaks. The command antenna may have represented an eleventh current peak of the same stroke or possibly a terminal of a second stroke. Since it would be unlikely for lightning to enter at the command antenna and leave just a few feet away at the fuselage, the trailing antenna was probably the other terminal in each case.) After the disruptive discharge, the engineer on board the aircraft observed a fire in the radio room at the antenna entrance, and immediately used a fire extinguisher to check and smother the blaze. On learning of the fire, the pilot headed the aircraft toward its base field and landed. Damage caused by the fire was "relatively minor" and consisted of burned upholstery, wiring, and lagging on the fuselage adjacent to the trailing antenna reel. However, so much smoke was caused by the fire that visibility in the radio room during flight was seriously reduced. The smoke spread throughout the fuselage, and even after landing smoke continued to escape from the rear of the plane.

Case 12: (110540B) Point of entry: nose portion. Point of emergence: mainly left wing tip. Damage: marker antenna burned free from front mast. Numerous puddle marks and one small hole (1/4 in.) in right side of nose portion of airplane and for approximately 3 feet back from nose portion. Small fused portion No. 2 blade right propeller. Approximately

4 inches fused section on left wing tip, approximately 12 inches back of navigation light. Fatigue "flowers" with 5-inch radius from greatest indication of fusion on tip (on upper portion of wing) with scorch marking just forward of fusion.

Case 13: Point of entry: nose. Point of emergence: rear tail cone at trailing antenna outlet. Damage: trailing wire antenna burned off at plug-in and also burned away inside of tail cone. Tube containing emergency trailing-wire antenna was kinked so that it was impossible to release. Knife switch of emergency antenna was broken. Tail cone looked like it was blown open, all rivets being gone for a distance of approximately 24 inches forward from tail light, which was hanging by its wires and was still lighted. There was an area approximately 1 foot square on top of the nose of the airplane on the left side of the center where the metal was blistered. (It seems possible that the discharge caused sudden vaporization of water which may have seeped into the tail cone during flight through rain and thus produced the explosive opening of the tail cone. Better sealing of possible openings for water to get in presumably would prevent recurrences of such effects. The opening of seams in the tail cone could result from rapid expansion of air due to the heat generated by the heavy discharge current, and melting and arcing in the narrow spaces of the auxiliary antenna release mechanism.)

Case 14: There was evidence of a discharge on the airplane near the outside air temperature bulb. Small holes were burned in the fuselage back of the temperature bulb on the left side of the cockpit between stations 20 and 63. (Holes afterward were plugged with 5/32-inch-diameter 17 SD BN rivets, and air-temperature bulb was replaced.)

Case 15: Point of entry: antenna fair-lead above cockpit. Point of emergence: trailing edge of left elevator. Damage: in addition to a blinding flash, a shower of sparks shot all over the cargo compartment companionway aft of the cockpit for several seconds. Binding post of radio-frequency change-over switch on rear of cockpit bulkhead was fused and blackened. Radio line was checked for further evidence of damage, but none was found. Operation of radio sets was not affected. A 1/4-inch hole was burned in the fabric trailing edge of the left elevator, a V-strip of dural at the same point was fused so intensely that part of this strip was melted completely away.

Case 16: British passenger airplane struck on May 9, 1932. Trailing antenna reeled out, but radio receiver switched off on account of static. Altitude, 2000 feet; visibility, several yards, the wing tip being invisible owing to soft snow which was falling and beginning to freeze on the windshield. About 30 seconds after switching off radio, a deafening explosion occurred in the wireless set behind the pilot, and pilot's seat was forced to the left of the cockpit, jumping the catch. Pilot regained position in front of controls immediately and throttled back all engines, placing aircraft in a gentle glide. Out of corner of his eye, pilot noticed a cloud of smoke clearing away while fragments of glass were falling in his lap. An intense draft was rushing through the cockpit. The pilot, on calling the copilot to shut the windows, found that of the eight panes, five had disappeared and the right front pane was starred¹ badly. The forward side pane on the pilot's side, which had been slightly open, was also badly cracked and slid right back. The engines were unaffected. The trailing antenna was burned off. The outside door of the wireless compartment was open, with the small window blown out, and the communicating door to the forward cabin was blown in about 1 inch against the jamb, and jammed. The aerial winch was shattered and a fire extinguisher was in two pieces. The ungrounded aerial was probably instrumental in causing the damage in the wireless compartment. The breaking of the windows and the jamming of the door obviously were due to violent changes of air pressure; but it is impossible to say whether this was due to the disruptive effect of the electrical current conveyed into the wireless cabin by the aerial or whether it was due to the explosion wave of the main lightning discharge. The latter is the more probable because the large cabins of passenger airplanes, which are made almost airtight to keep out the draft and the noise, react with great force to rapid change of outside pressure. (The foregoing description is essentially an excerpt from a report of the accident given by the pilot and included in the publication with comments by G. C. Simpson, "Lightning and Aircraft," Great Britain, Meteorological Office, Air Ministry, Professional Notes, No. 66, London, 1934.)

Case 17: Point of entry: probably the trailing antenna. Point of emergence: right wing tip. Damage: (1) radio equipment - as indicated in quotation below; and (2) trailing edge of right wing tip - holes burned through aluminum skin 0.032 inch thick, with number of holes and diameters as follows: 4 holes with diameter 1/4, 3/16, 1/8, and 1/16 inch, respectively. Several pits ranging in

¹Fractured.

size from 1/8 to 1/32 inch in diameter melted in outer surface. In the interior of the wing, the ribs and skin adjacent to the damaged area were spotted with portions of molten aluminum. The Flight Radio Officer reported:

"The aircraft had been flying in a cloud for 3 or 4 minutes, and there had been moderately heavy static in the headphones during this period. I did not notice whether the static discharge spark gap was operating. Suddenly there was a blinding blue flash and an extremely loud noise, similar to an explosion. Both the flash and the noise lasted for but a very small fraction of a second. The flash seemed to originate at the trailing antenna binding post on the transmitter panel. No previous electrical disturbances had been noticed except the static in the headphones. Although wearing the headphones, I did not feel any electrical shock when the lightning struck.

"The trailing antenna either was broken off or melted off at the point where it entered the bottom end of the fairing tube beneath the fuselage. Two porcelain insulators were broken off. One was the insulator supporting the static discharge gap, and the other was the trailing antenna post on the transmitter panel. Both ends of the lead-in wire for the trailing antenna were burned and partially melted. Several wires and contacts inside the transmitter associated with the trailing antenna and the channel switch on the side which was being used were melted. The dynamotor was not on and the transmitter was not being keyed at the time of the discharge. The charge evidently traveled through the conduit into the AVR-7HSS antenna control panel, melting one wire and charring the inside of the unit. The antenna ammeter was damaged somewhat but not burned out. Apparently no tubes or coils were damaged, either in the transmitter or the receivers. The master switches had been shut off by the captain, and radio communication was re-established as soon as these were turned on again."

The reports cited in the foregoing discussion refer essentially to all-metal airplanes. It is thus apparent that the damage from electrical discharges in the case of aircraft with electrically conducting skin, and all metallic parts well bonded, is ordinarily not of a serious nature.

However, aircraft which do not have completely electrically conducting skins (such as fabric) or which have deficient electrical bonding between metallic parts are subject to much greater damage, while greater hazards are entailed for the occupants of such aircraft.

This is illustrated by the following report:

Case 18: A formation of nine SU-type U. S. Navy training airplanes was flying in a division Vee at an altitude of 2500 feet. There was a thunderstorm of moderate dimensions about a mile to the westward, and a few scattered clouds about 500 feet above the formation. A bolt of lightning to the left was observed to start downward, then curve directly through the formation. There was a blinding flash and the bolt of lightning was seen to strike the right lower wing tip of No. 2 airplane in the first section of the formation. The damage wrought to this airplane, as determined by investigation after return of the formation to its home landing field was: approximately 4 square feet of fabric on outboard edge of lower right wing torn and ripped clear of wing. Four former ribs on leading outboard edge of lower right wing destroyed; the metallic clip securing the bonding wire clip bolt, which holds the interwing brace wire to the outboard compression rib, was burned and fused. The main spar cracked a length of about 18 inches from the outboard end.

The damage to No. 1 airplane of the first section of the formation was: small hole torn in fabric on left elevator; no damage to metal structure of elevator was sustained.

The damage to No. 3 airplane of the first section was: approximately 1 square foot of fabric torn clear of right edge of right lower wing tip; one former rib on leading outboard edge of right lower wing was cracked.

The damage to No. 1 airplane of the second section of the formation was: small hole torn in fabric on leading edge of right lower wing outboard of outboard compression rib.

The damage to No. 2 airplane of the second section was: small hole torn in fabric on leading edge of right lower wing outboard of outboard compression rib; no damage to wooden structure of wing was sustained.

No other airplanes of the formation were damaged. The personnel of the flight suffered no injuries or ill effects.

The airplanes of this formation were not equipped with radio. However, the right wings, both upper and lower, contained five wires, each of which would have formed wing loops

had they been connected. It is not believed that the lightning passed along these wires in view of the fact that there is no evidence of arcing at the ends.

There is a bonding wire which starts at the lower wing forward hinge fitting at the fuselage and runs down the after side of the forward spar, aft along the outboard compression member and returns along the after spar, inboard to the after-hinge fitting. All internal brace wires and metal fittings in the wing are connected to this bonding wire.

It is believed that the actual bolt of lightning entered No. 2 airplane in the first section of the formation via the left wing and fuselage, thence into the main bonding wire of the lower wing. At the point of junction of the forward outboard internal brace wire fitting and the bonding wire, the copper bonding wire fitting was broken with a fresh break. It is thought that the electrical charge left the bonding wire at this point and burst through the leading edge of the wing, splitting the spar, demolishing the former ribs, and ripping the fabric. It is presumed that the lightning failed to reach the upper wing because the bulk of the metal in the fuselage is closer to lower wing hinge fittings.

It is believed also that the damage to the other airplanes was of a much less degree because the electrical charge which passed through them was less, and, furthermore, that if the bonding in all the airplanes had not been complete, serious damage might have resulted.

16. EFFECTS ON PILOTS

The effects on pilots of atmospheric electrical discharges to aircraft may be divided into: (a) visual, (b) aural, (c) electrical, and (d) psychological. These are now considered in turn.

(a) Visual. - The discharge generally takes the character of a blinding flash the effect of which is ordinarily of rather brief duration. Consequent upon the flash is usually a temporary blindness lasting from a few seconds to perhaps 3 minutes. The more severe effects occur during the hours of darkness. (The most severe case reported involved a copilot who was unable to see for 8 minutes after the discharge, although the pilot of the same airplane had normal vision 10 seconds after the discharge.) The temporary

blindness is followed by slightly impaired vision, returning to normal usually within a time ranging from a fraction of a minute to possibly 10 minutes.

The effect of the flash on the pilot's vision depends on a number of factors which may be enumerated briefly as follows: The light adaptation of the eyes is greatly determined by the brightness of the cockpit lights prior to the discharge; the illumination outside of the airplane prior to the discharge; the length of time the pilot has been looking at the cockpit lights, or outside daylight or darkness. Also effective are the directness of the pilot's vision on the cockpit lights, outside illumination, and the lightning flash at the instant of the occurrence of the latter as well as the shielding of the pilot's eyes by opaque objects or dark-colored goggles.

In the daylight, the temporary blinding effect lasts for only a few or several seconds. If the cockpit lights are turned up full bright and the pilot's eyes are adapted to the illumination, the effect is also of relatively short duration, although at night probably longer than in the daylight. Shielding of the eyes by keeping the head inclined and low in the cockpit affords great alleviation from the harmful effects of the flash. The nearer or more directly in the line of sight is the flash, and the more wide-open the pupil of the eye from looking into darkness, the more likely it is that the temporary blinding effects will be of longer duration.

The slight, temporary impairment of vision following the temporary blinding presumably has the character of an apparent purple haze before the eyes, and generally also involves after-images of the flash on the retina for a brief time. The pilot cannot see so well in darkness or dim light, nor is his visual discrimination normal during this interval. Bright lights cannot be tolerated until vision returns to normal.

(b) Aural. — The electrical discharge usually is accompanied by a sound the loudness of which within the airplane may have various degrees of intensity, described by pilots in terms like the following: dull thump; sizzlelike arc weld; snapping sound, not like thunder; sharp crack, no roar; muffled explosion; sound like a shotgun fired; sound like rifle fire; sharp report, like 32-caliber gun; loud crash; fairly loud boom; sound like an explosion; severe detonation like a 75-millimeter gun fired; sound similar to a 15-inch gun discharge; sound similar to high explosive; very bad explosion; loud explosion; sharp roar; thunderclap;

terrific report; violent noise; resounding crash which deadened hearing senses; deafening crash of thunder. In a number of cases, no appreciable sound — or sound of such character as to merit comment — was heard accompanying the electrical discharge.

The sound ordinarily does not seem to cause more than a momentary loss of hearing and some confusion. The latter is influenced partly by the bright flash and other psychologically disturbing factors attending the discharge. (See discussion under (d) Psychological.)

Illustrative of the most extreme effect reported as due to the thunder is the following excerpt taken from remarks rendered by a passenger on an airplane which suffered a discharge: "About 15 minutes out of (City) the ship passed through a very violent weather front encountering severe rain and sleet. Immediately upon passing through the front area and after the rain and sleet had stopped, fire streaks approximately 8 inches long were observed in the propeller disk areas at approximately the propeller tip radius. This condition was observed by the writer on the right propeller while Mr. X, who was sitting on the left side of the airplane noted the same condition on the left propeller. Approximately 1 minute after this discharge of St. Elmo's fire, a violent electrical discharge took place from the airplane to the surrounding atmosphere. A large ball of white fire approximately 6 to 8 feet in diameter appeared to envelop the right engine nacelle and engine propeller unit. At the instant this fire appeared there was a resounding crash which deadened the hearing senses. Immediately after the discharge and noise which lasted for a duration of approximately 2 seconds everything seemed to stand still and there was a lull uninterrupted by noise. This, I believe was due to my sense of sight and sense of hearing being temporarily impaired and not due to any actual stoppage of airplane engines. I believe that the engines continued to operate normally during this lull and immediately I regained my full equilibrium I noticed that the pilot had turned back and was returning to (City). Mr. X told me that he had noticed the same sort of discharge at the left wing tip of the airplane and that he experienced the same feeling as myself with respect to senses."

Another effect on the hearing can result from a very sharp click in the earphones due to the surge of current in the radio circuit when the antenna or radio forms part

of the discharge path. It is thus possible to receive acoustical shock if the earphones are closely fitted, the saturation characteristics of the vacuum tubes in the radio receiving set are not such as to limit greatly the intensity of acoustic disturbances produced electromagnetically in the head receivers, and the earphones do not have a suitable stop to prevent excess motion of the diaphragm due to the discharge-current surge. Suddenly increased pressure above a certain value produced in the ear canal by the abrupt metallic earphone click can be uncomfortably loud, accompanied by momentary dizziness and ringing in the ears (tinnitus). In extreme cases, unconsciousness may result. This seems to have happened in one or two cases. In one other instance the pilot reported that his ears hurt for 15 or 20 minutes, probably due to having earphones on at time of the discharge. Wearing of a head set close to the ears when circumstances indicate a discharge may be imminent is therefore considered inadvisable. Earphones with appropriate protective features are desirable.

(c) Electrical.— Pilots have reported seeing sparks inside of the cockpit on a few occasions, about the time of the discharge, but in no case was any serious harmful effect indicated, where an all-metal aircraft with all metallic parts bonded was involved.

The reports on these cases are as follows:

Case 1: Pilot recalled that once when near the edge of a thunderstorm an unusually large spark of static electricity jumped from one of the engine controls to the hand of the Second Pilot over a gap of some 6 or more inches, but he did not know whether a lightning discharge was occurring at the same time near the airplane. (No injury to the Second Pilot was indicated in the report.)

Case 2: Pilot felt shock on hands and feet, with blinding flash on nose in front of left cockpit window. One engine stopped for a few seconds: no apparent damage noticed afterward.

Case 3: The actual lightning appeared to have hit on the nose and splashed fire in all directions. First Officer felt slight shock in his hand where he was holding the metal part of the chair.

Case 4: No indication of lightning until attack on nose of airplane for 20 to 30 seconds. Propellers throwing off streamers for 10 to 15 feet and halo around charge entering nose as far as (pilot) could see in the overcast. Spark leaping from instrument panel to cowl above, then discharge like engine backfire with blinding flash. Pilot stated he was blinded temporarily and arm nerves or muscles pained.

Case 5: "The flight engineer had his hand resting on the arm of the captain's seat, and after the incident discovered the hair had been singed from the back of his hand."

Case 6: Prior to entering cloud bank, static was evident in airplane. Pilot received a slight shock at water cooler while drawing a cup of water. Heard reports from members of the crew of static crackling in bedclothing.

Case 7: Radio officer saw a blinding blue flash in the radio compartment. This was due to flashover at the trailing antenna binding post on the radio transmitter panel, when current originating as a disruptive discharge apparently traveled from the trailing antenna through the lead-in wire to the transmitter antenna control panel. The current after arcing over from the binding post flowed through the airplane to the right wing and out the wing tip. No electric shock was sustained by any personnel on the aircraft. (For details, refer to case 17 of sec. 15.)

Case 8: Pilot claimed he observed sparks inside of the cockpit on right side near rudder pedals, occurring at the same time as the disruptive discharge. Their color was described as red, and they seemed to go from control pedestal to the right side of the aircraft. (The pilot's eyes were focused on the instruments at the time of the discharge.) No shock was felt by either pilot or copilot, and no damage within cockpit was reported.

Case 9: Pilot claimed he observed a spark inside of the cockpit across the face of the gyro-horizon on the automatic pilot. It appeared to be white and 1 to 2 inches long. No shock was experienced. The pilot had his eyes focused on the automatic direction finder and the copilot had his focused on the control panel. The phenomenon was simultaneous with the disruptive discharge which appeared to come from above the nose of the fuselage, striking the nose on the upper side and at the same time spreading out in branches covering the entire nose section of the aircraft.

Case 10: Pilots stated they observed a "red fire" at the same instant as the disruptive discharge, located "back of and beneath the instrument panel." It appeared to be "just a flash," like a "flame or fire." No shock was experienced by the crew. No smoke or burning of equipment inside of the cockpit was detected. The pilots stated they were looking "dead ahead" at the instant of discharge. (The disruptive discharge entered at the nose of the fuselage in front of the windshield causing scorch and pit marks over an area of 3 square feet. The discharge emerged from the trailing edge of the left elevator adjacent to the outboard end of the flettner, causing some melting of the thin edges, scorching and tearing loose about 1 square foot of fabric from the elevator.)

It would appear from the foregoing statements that some of the cases in which sparks were reported to have been observed inside of the cockpit may possibly be attributed to an optical illusion. In at least one of the above-cited cases, static electricity produced by friction within the airplane during flight in dry air appears to have been the explanation of the phenomenon. (See case 6.)

However, in situations where radio equipment is involved, other considerations are necessary. Aircraft with all-metal skins and with all metallic parts properly bonded act like a Faraday cage. Consequently, there can ordinarily be little difference of potential (voltage) between different points on the interior bonded metal surface of the airplane. A considerable difference of potential may exist in the radio equipment when charges are conveyed into the airplane by the aerial, but the maximum difference which may be effective outside of that is greatly limited by the insulation strength in the radio or by the lightning arrester gap. Where there is a short gap over which the discharge may flash to conducting parts bonded to the metal framework of the airplane, or where there is a weak place in the insulation through which the current may arc to a bonded part, such an event usually occurs, generally at the fair-lead, lightning arrester, or within the radio equipment. Thus, after flashover begins, the voltage difference between the aerial conducting the charges within the airplane and the metallic framework is probably held to a value of the order of 500 to 1000 volts. Owing to the insulation between the aerial and the pilot, as well as between the pilot and the framework, it is doubtful whether a seriously harmful potential difference could be brought to bear between the pilot and the specified conductors unless there were deficient bonding of the metallic parts.

In the case of a discharge current having a very steep wave front, that is, one which rises extremely rapidly to its maximum value, a considerable difference of potential may exist between neighboring points in the conductor carrying the current as the wave front passes. A person then making contact with the conductor at two widely spaced points (as with hands while arms are outstretched), may thus receive a shock, but the wave front travels so rapidly that the time interval (of the order of ten millionths of a second) during which current flows through his body is of extreme shortness. The effect of a shock from this source is therefore inconsequential.

Shocks from static in the interior of the airplane collected on nonconducting parts cannot have any important effect.

Where bonding between metallic parts is defective or lacking, or where the aircraft is principally constructed of nonconducting materials (as fabric and wood), large differences of potential may be established during an electrical discharge through parts of the aircraft. Disruptive effects occur where nonconducting materials are involved. Fires may be caused as a result of arcing at points of faulty bonding, and shocks may be experienced.

In one known instance of a wood-fabric constructed airplane (1922), failure to bond in the control column after repair resulted in a shock to the pilot via the headset microphone when the aircraft was struck by lightning. The pilot lost consciousness but regained it in about 1 minute and resumed control of his airplane before it reached too low an altitude.

(d) Psychological.— Psychological effects are not always due to the lightning and thunder. Sometimes they result from the severe characteristics of thunderstorms in which the lightning may be encountered. Thus when an aircraft flying at considerable speed enters an extremely turbulent region within a strongly developed thunderstorm, momentary panic may seize the persons on board in view of the conditions experienced. For a very brief time the airplane then possibly undergoes violent rolling, pitching, and yawing motions, accompanied by severe jarring and racking of the craft and its controls, in addition to violent air-speed fluctuations and irregular accelerations, all of which are attended by noises of unfamiliar character and varying intensity. Usually, the space in which such severe turbulence

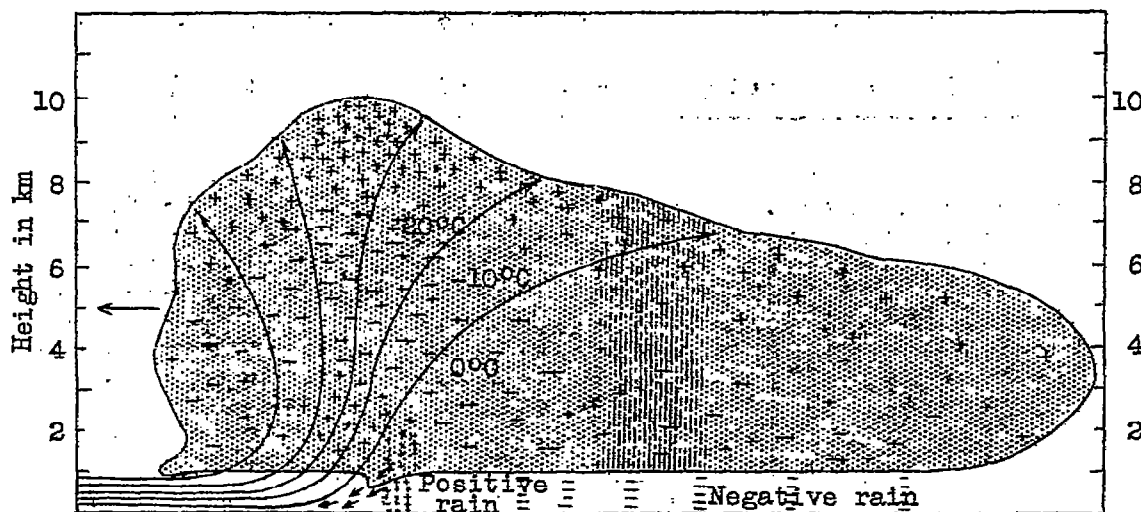
occurs is narrow, appearing as a rule in the transition zone between adjacent vertical currents having markedly different vertical velocities. (See sec. 10.) The brilliant flash of the discharge, the usually accompanying loud noise, and the concussion generally frighten the pilot for an instant and produce momentary confusion. He becomes startled and his choice reactions are slow and faulty for a short time interval. If the flash occurs at night and the temporary blinding effect is severe, the pilot is under the handicap of not being able to see his instruments or controls for a brief period. For this reason, it is desirable to have the automatic pilot ready to engage, if not already engaged. (Important: See cautions, sec. 20, par. 8.)

When the discharge is of the steep, wave-front type, the thunder is likely to be of relatively greater intensity than otherwise. Under these circumstances, the explosive expansion wave of the thunder released in close proximity of the airplane produces a concussion where the intense sound wave strikes any resisting object. That is, the sudden pressure wave, by impinging on the nearest airplane parts with considerable force, causes a sensation of being jarred or of experiencing a severe bump. The eardrums and other parts of the body are affected in a similar manner, except that the intensity of the pressure wave falls off rapidly with distance from the discharge channel, so that no harmful effects on the hearing have been reported as yet from this cause. Where the quantity of electricity which passes through the discharge channel is relatively great and the wave front of the current is of considerable steepness, the optical and acoustical phenomena associated with the discharge are bound to be of high intensity. The concussion, in conjunction with the other phenomena may, under these unusually severe conditions, produce on the pilot a sensation of being stunned. This is quickly overcome as he realizes the situation and commences to resume control of his aircraft.

17. DISTRIBUTION OF ELECTRICITY IN THUNDERCLOUDS

Electrical conditions in certain regions of thunderclouds are more conducive to the evolvment of an electrical discharge to an aircraft than in other regions. In order that the pilot may seek to avoid the former regions, it is necessary for him to have some understanding of the distribution of electricity in thunderclouds and of the nature and causes of lightning discharges.

Studies of atmospheric electricity by various means have shown that generally the upper portion of the typical thundercloud has a concentration of positive electricity; while the major part, at least, of the lower portion has a concentration of negative electricity. Often apparently, there is also a small region near the base of the thundercloud and in the rain falling out of this region where there is a further concentration of positive electricity. This combination of distributions of electricity is illustrated in the accompanying diagram, based on the work of Simpson and his collaborators (references 10 to 12). Valuable data on the subject also have been derived from the investigations of Workman and Holzer (reference 13) and others. In studying the diagram of Simpson and collaborators, it may be recalled that 1 kilometer = 3280 feet, and that the indicated temperatures in degrees centigrade converted to degrees Fahrenheit are as follows: $0^{\circ}\text{C} = 32^{\circ}\text{F}$ (the normal freezing point of water); $-10^{\circ}\text{C} = +14^{\circ}\text{F}$, and $-20^{\circ}\text{C} = -4^{\circ}\text{F}$.



Generalized diagram showing air currents and distribution of electricity in a typical heat thunderstorm.¹

¹Individual actual thunderstorms generally do not look like this, but possibly some thunderstorms do. The distribution of charges in actual cases may differ somewhat in detail from that shown. The lower, small region of positive charges does not always seem to be present, according to Workman and Holzer (reference 13).

The small, positively charged region near the base of the cloud may not always be present, but the positively charged region near the top of the cloud and the lower negatively charged region are invariably found.

The data collected by Simpson and his collaborators indicate that the temperature at the center of the electrically charged regions in question was approximately as follows:

Designation of region	Location and sign of electrically charged region of typical thundercloud	Average temperature of center		Observed temperature range of center	
		(°F)	(°C)	(°F)	(°C)
P	Upper positive	-9	-23	+10 to -36	-12 to -38
N	(Low) negative	+20	-7	+46 to -2	+8 to -19
Q	Lower positive	+35	+2	+43 to +16	+6 to -9

Between the regions where electrical charges of opposite sign are concentrated are zones where the electric field intensities tend to have maximum values. Restating this in terms of the potential gradient (that is, voltage difference per unit distance in the direction positive electrical charges would be driven by the existing electric field), it may be said that the potential gradient tends to a maximum somewhere between the regions of heaviest concentration of electrical charges of opposite sign. The zones of maximum potential gradient normally will lie in the general vicinity of the boundaries between the charged regions but not exactly at the boundaries unless certain conditions of symmetry prevail (such as equal quantity of electrical charges in each region, uniform distribution of charges in equally sized spherical regions, etc.). The zones of maximum potential gradient will be the areas where an electrical discharge to an aircraft can be most readily initiated by the effects of the presence of the aircraft and the static charges residing on it (as manifested by intensity of St. Elmo's fire or precipitation static). (See sec. 12.)

The approximate average temperatures and altitudes at the centers of the charged regions in thunderclouds and of the estimated zones of maximum potential gradient in a vertical

line through the centers in question are shown in the following table, based on Simpson and collaborators' data for Great Britain.

Designation of region	Region	Average temperature (°F)	Average altitude (ft)	Average temperature (°C)	Average altitude (km)	Remarks
P	Center of upper positively charged region	-9	20,400	-23	6.2	Estimated
Z _{PN}	Zone of maximum potential gradient between P and N	7	16,500	-14	5.0	
N	Center of (low) negatively charged region	20	13,200	-7	4.0	
Z _{NQ}	Zone of maximum potential gradient between N and Q	30	9,900	-1	3.0	Estimated
	Freezing level	32	9,500	0	2.9	Zone of maximum potential gradient in the horizontal direction ¹
Q	Center of lower positively charged region	35	8,300	2	2.5	
Z _{QE}	Zone of maximum potential gradient between Q and earth	41	6,600	5	2.0	Estimated

¹ Between Q and the negatively charged region around it.

The foregoing data are substantially consistent with the average altitude and temperature values shown in sections 5 and 6, on the basis of the statistics derived from reports of actual electrical discharges to aircraft.

The preceding table and the diagram on page 51 indicate that there may be expected at least four zones in a typical thundercloud where the potential gradient tends to be a maximum and the chances of experiencing an electrical discharge to an aircraft are greatest. These four zones are predicated on the assumption that the lower, positively charged region invariably exists in the base of the cloud and in the rain falling from an active low-lying positive center.

It should be noted that the maximum potential gradients can have vertical, horizontal, or oblique directions, depending on the location with reference to the charged centers involved. Inasmuch as thunderclouds are subject to violent convective activity and turbulence, a considerable amount of shifting of the charged regions can be expected, so that perfect uniformity of location of the most hazardous zones is not likely to prevail.

Workman, Holzer, and Pelsor (reference 13) conducted a study of the time histories of thunderstorm charge distribution during three storms occurring during the summer of 1940 in the vicinity of the Albuquerque, New Mexico, airport. To determine the distribution, they used eight synchronized recording electrometers arranged in a particular pattern over a field 1.6 kilometers (about 1 mile) above sea level. The instruments, which had a time-resolving power of 0.01 second, gave simultaneous records of the changes in the surface potential gradient caused by lightning strokes. The quantities of electrical charge contained in the cloud charge centers and the locations of the centers in the space above the earth with reference to given coordinate axes were computed, under certain simplifying assumptions, by means of certain well-known relationships derived from the theories of electrostatics.

The three authors cited summarized their conclusions as follows, with regard to the lightning strokes and the charge centers of the three thunderstorms studied:

1. The average charge neutralized by a stroke element is 6.5 coulombs and the average value of the charge neutralized by a lightning stroke (the sum of the separate charges

neutralized by the various elements of the stroke in the case of repeated strokes¹) is 24 coulombs.

2. The weighted average height of the negative charges was 5.2 kilometers and of the positive charges was 5.8 kilometers above the surface; that is, the mean vertical separation of charges was less than 1 kilometer. The heights actually ranged between 4 and 7 kilometers and included the region where the temperature is between -5° and -25°C .

3. Horizontal separations between charges involved in an intracloud stroke varied between 1 and 10 kilometers. The weighted mean value was 3 kilometers.

4. Cloud-ground strokes were observed only on August 15, and all of these strokes transported negative charges to the ground. This result is in agreement with those of previously reported observations.

5. A study of the distribution of charges showed that it was possible to identify definite regions of charge that persisted for intervals from 10 to more than 30 minutes. These regions traveled with moving storms and had approximately the same velocity as the heavier rain sheets. In the one case when it was possible to compare the average velocity of the charge regions with the average wind velocity at the charge levels in advance of the storm, the two velocities agreed within 10 percent.

6. Evidence supplied by the storm of September 10 (1940) showed that the negative charges were in the region of the updraft and that positive charges were displaced upward and away from the negative charge in this region. Further evidence was found in the storm of August 15 (1940). The negative regions were coherent and positive charges were found on both sides of the negative regions. The evidence is consistent with the hypothesis that the more coherent region was associated with the updraft.

7. Cloud-ground strokes were more frequent in the earlier stages of the development of an active region of the thunderstorm. As an active region aged, the lightning strokes became predominantly or exclusively intracloud strokes. The aging was also characteristically associated with a decrease in stroke frequency.

¹The 24 coulombs refer to a multiple lightning stroke consisting of several repeated strokes along essentially the same channel. See appendix VII.

8. The maximum vertical potential gradients existed immediately above and below the charge concentrations, and the maximum horizontal gradients existed at the same level as the charges.

9. One of the principal dangers to aircraft in thunderstorms is the possibility that the craft may become part of a lightning channel. This possibility is greatest in regions where the potential gradients are greatest. The present investigation showed that these regions are most likely to occur where the temperature is between -5° and -25° C.

18. MECHANISM OF DISRUPTIVE DISCHARGES INITIATED BY AIRCRAFT

General Discussion

The records previously cited in regard to the actual effects of disruptive electrical discharges upon aircraft indicate that some have been of the high-current, steep-wave-front, short-time variety, and some (perhaps a majority) have been of the low-current, gradual-wave-front, long-time variety.

It is apparent that in some instances the aircraft has happened to be in the path of a lightning discharge initiated at some distant point in a thunderstorm where the critical breakdown potential gradient was attained. These are purely accidental occurrences, in which the aircraft played no part in starting the discharge.

In other cases, it appears that the aircraft was instrumental in producing the disruptive discharge. (See sec. 7.) The mechanism by which this takes place has not been investigated directly in the laboratory, but from what is known of the nature of spark discharges it may be presumed that the mechanism that prevails is essentially as outlined in the paragraphs succeeding the next.

First to recapitulate briefly the conditions:

So far as can be judged from reports rendered by pilots, the disruptive discharges of this latter type which have occurred to aircraft took place either while the aircraft was flying within a cloud or precipitation or while it was just entering or emerging from a cloud. In practically every instance the cloud was of a cumuliform character.

generally cumulo-nimbus, sometimes cumulus, and rarely strato-cumulus. Some of the former were active thunderstorms. Within the clouds either rain, rain plus some form of frozen precipitation, or one or more forms of frozen precipitation were encountered, generally at temperatures within the range $32^{\circ} \pm 8^{\circ} \text{ F.}$

From what has been stated in section 17, it may be expected that the aircraft fairly often will be within a region of relatively high potential gradient when subjected to the conditions outlined above.

At the scene of the disruptive discharge, the potential gradient immediately prior to the appearance of the aircraft in the locality and before the discharge may have been considerably less than the critical breakdown potential gradient.

However, the aircraft by its very presence may increase the potential gradient manyfold, as explained in section 12. One process which invariably tends to accomplish this to an important extent is the distortion of the electric field by induction upon the conducting outer skin of the aircraft (see paragraph numbered (2) and following, in the above-mentioned section). This is most likely to happen with notable consequences in a space where the initial potential gradient is already quite high, as between two contiguous, highly charged cloud regions of opposite polarity, or in the immediate vicinity of a single region having a great concentration of electrical charges of one predominant sign. It is possible under these circumstances for a disruptive discharge to be "triggered" by the aircraft, provided (1) that the critical breakdown potential gradient is reached at or near the aircraft, and (2) that once the disruptive discharge is initiated at such a point continued propagation of the discharge streamer is assured by a sufficiently high average potential gradient in the space between the oppositely charged cloud regions or between a single charged region of one sign and another restricted region (whether of the cloud, space charge, or earth) with predominately opposite charge.

To illustrate the latter situation, one locality where a high potential gradient may be encountered is between a cloud region containing a myriad of condensation particles carrying electric charges mainly of one sign, and a space charge containing mostly oppositely charged ions (i.e., charged particles approximately of molecular size, or

clusters of a relatively small number of molecules carrying a charge). Such a locality may be found just outside of certain parts of cumulo-nimbus clouds, and especially well developed or aged thunderstorms. These clouds apparently develop space charges along their bases, sides, and sometimes tops in various stages of their life cycle. This may possibly explain some cases of disruptive discharges which have occurred to aircraft just as they were entering or emerging from a cumulo-nimbus cloud or thunderstorm.

Probably of considerable importance in the phenomenon of disruptive discharges initiated by airplanes is the modifying influence exerted by acquired charges. Suppose that an aircraft passes through a cloud or precipitation region consisting of condensation particles carrying charges predominantly of one sign, and suppose further that it acquires a considerable quantity of charges of that sign by the processes outlined in section 12. Consider the aircraft to retain much of its charge despite loss by corona and to effect rapid approach toward a nearby cloud or precipitation region carrying charges principally of the opposite sign. Then, owing to the opposite polarities, this produces a sudden intensification of the potential gradient in the narrowing space between them. This augments to some extent the increase of potential gradient resulting from distortion of the existing electric field by the aircraft, as previously explained. The local potential gradient near the extremities of greatest convexity may thus be heightened to a value possibly exceeding the sparking potential gradient. Contrariwise, if the aircraft and the nearby charged region being approached were charged alike in sign electrically, there would be a depression of the local existing potential gradient which tends to hamper the development of a disruptive discharge.

Effects of Size of Aircraft

The size of the aircraft involved plays an important role in determining the frequency of disruptive discharges, whether natural lightning strokes encountered by chance or discharges initiated by the aircraft themselves. Thus, the larger an airplane, the greater the space in which natural strokes or their branches may be encountered, and the greater the frequency of experiencing them. It is to be expected that a natural stroke occurring within a distance of the aircraft equal to its dimensions will have a pronounced tendency to include the aircraft in its path.

This effect probably is not of so great importance statistically as the efficacious process whereby large aircraft may initiate disruptive discharges more frequently than smaller aircraft, other conditions being equal. (In reckoning the size of the airplane the trailing wire or antenna must be taken into account.) With increase in size of aircraft there will be an increase per unit time (1) in quantity of space and in number of precipitation or dust particles brought under the influence of the airplane, and (2) in number of such particles coming into contact with the exterior surface of the airplane, under uniform conditions regarding the particles, airspeed, air density, electrical field intensity, and so forth. Furthermore, the electrical capacitance of the airplane (quantity of charge it may hold at unit potential) will undergo an increase with growth in size of airplanes, assuming similar geometrical configurations.

This implies that larger aircraft flying in snow, ice crystals, dust, and so forth, may have heavier charges of static electricity generated and residing on them by triboelectric effects than smaller ones, provided (1) that the most sharply convex protuberances (such as trailing wires, burrs, etc.) are of equal radius of curvature in all aircraft, and (2) that the potential gradient at which such protuberances of similar nature go into corona is the same for all aircraft.

Consider a large and a small metal airplane of similar geometrical shape flying in identical conditions with reference to the electrical field intensity, precipitation, dust, airspeed, air density, and so forth. Then, the external electric field of given intensity may induce steeper local potential gradients near the specified protuberances on the larger than on the smaller aircraft. This result is produced because there may be more free charge available on a larger airplane than on a smaller one, and because the induction of charges on the extremities of the airplanes tends to be more effective the farther apart the extremities (such as wing tips or nose and trailing wire) are from one another and from the main body of the airplane.

In brief, then, the potential gradient at certain favorable extremities will tend to be elevated to a greater extent on the larger airplanes than on the small ones, as a result of induction by external electrical fields. From this, it may be concluded that physical reasons exist which tend to cause more frequent development of the critical (sparking) potential gradient by larger than by smaller airplanes, under otherwise equal conditions.

Effects of Airspeed

The speed of the aircraft involved may play a role of more or less influence in determining the frequency of disruptive discharges of the type initiated by the airplanes themselves. In section 12 under "Effects of Speed," it was pointed out that at least two phenomena tend to intensify the potential gradient near an airplane in flight through charged cloud or precipitation particles. These result from the motion of the aircraft relative to the particles, and are: (a) the forced coalescence of like-charged water droplets, snowflakes, and so forth, which gives the merged particles a greater potential than the smaller particles of like sign originally present; and (b) the ram-action of the airplane which by crowding of particles of given sign into a smaller space intensifies the potential gradient. The greater the speed of the aircraft, the more pronounced will be these effects, and the more particles will be brought within the sphere of influence of the aircraft, with similar results.

The mechanisms just outlined will act to produce a maximum steepening of the potential gradient when an airplane flies toward a nearby highly charged cloud region or space charge of one predominant sign electrically, while it thrusts its way through an assemblage of highly charged cloud or precipitation particles of opposite sign. Thus, in such zones of generally steep potential gradient the gradient will be made more steep by the stated mechanisms, and perhaps be caused to exceed the critical (sparking) value near the aircraft, thereby leading to the development of an electrical breakdown of the field.

If the signs of the electrical charges had been alike in the charged region and the cloud or precipitation particles considered above, the effect of forced coalescence and ram-action would have been to diminish the potential gradient. Circumstances such as those just predicated generally are productive of and associated with slight potential gradients compared with those which prevail in the first-mentioned case

¹To simplify the discussion through avoidance of the need for defining the direction of the potential gradient, direction of flight and prevailing field intensity has been specified with respect to oppositely charged or like-charged regions or assemblages of particles carrying electrical charges.

which involved a zone of high field intensity between nearby charged regions of opposite polarity. An electrical breakdown is not very likely in a space of weak potential gradient, and less so in such a space with the gradients further weakened by the mechanisms described.

From the foregoing considerations, it is concluded that increase of airspeed is conducive to greater probability of development of the critical potential gradient in zones of pre-existing relatively steep gradient. Airspeed may therefore possibly be a factor of some importance in the mechanism of those disruptive discharges which are initiated by aircraft.

Streamer Mechanism

Before the critical potential gradient for a disruptive discharge is attained, corona discharges are generally occurring from various parts of the aircraft, for they start at considerably lower gradients than disruptive discharges. The current conveyed by the coronas is very weak and cannot cause burns in the metal skin, despite the intensity of radio interference from so-called "precipitation static" or otherwise, as outlined in section 12.

However, when the critical potential gradient for a disruptive discharge is achieved in the immediate vicinity of the exterior of the aircraft, local breakdown occurs in the form of long luminous streamers usually extending from the extremities of the airplane or the propeller tips. These streamers are probably essentially similar to the lightning "pilot streamer" described in appendix VII. The path blazed by the pilot streamer is largely controlled by the local potential gradient.

In a cloud or in precipitation, the path very likely will be determined by the configuration, concentration, and charges of the particles, for in an intense electric field glow discharges and sparking may occur from the particles (reference 4). Thus, glow discharges between adjacent droplets driven close together by the ram-action of the airplane may hasten a breakdown and aid in establishing the path of the streamer.

As found in the laboratory study of sparks (references 14 and 15), the leader strokes may be negative leaders or positive streamers. In the case of the negative leaders from the airplane the airplane would be of negative polarity. When a spark (disruptive discharge) passes, then at some point in the field where the potential gradient is sufficient, one

electron (here presumably from near the aircraft) is impelled by the strong field intensity to accelerate at a high rate. On making impacts with numerous neutral molecules and atoms the electron ionizes them, thereby liberating other electrons. These, in turn, are driven forward by the field to ionize other neutral particles, and so on, repeatedly. In this manner, an avalanche of electrons is created. Owing to their high mobility¹ they leave behind a concentration of positive ions, which constitute a space charge. These ions possess a much smaller mobility than the electrons and therefore move much more slowly and diffuse to a lesser extent. The cumulative ionization therefore takes place in a narrow path lying in the field direction. The electrons tend to diffuse laterally somewhat as they progress. To the rear of the electron avalanche the attraction of the positive ions tends to hold them back, an effect most pronounced on the hindermost. Here there is a weakening of the potential gradient.

The positive space charge temporarily steepens the potential gradient on the side toward the negatively charged cloud or airplane, until the ions are swept to the latter or are left behind by the moving aircraft. Analogously, the electron avalanche steepens the potential gradient near its tip on the side toward the positively charged cloud region which it is approaching.

While the electron avalanche continues to ionize neutral particles in its path, under the impetus of the electric field, it produces possibly four or more times as many photons² as it did ions (reference 14). These photons radiate in all directions at the speed of light, and a certain fraction will ionize some of the air molecules. The electrons liberated by this process produce fresh avalanches of electrons.

Near the head of the initial electron avalanche moving toward the positively charged cloud, the leading electrons and also the photons created there produce ionization in advance of the avalanche tip. At this point the potential gradient is locally steepened, so that the electrons are driven on, ionizing further, producing more electron avalanches and leaving positive space charge behind. This attracts and

¹Mobility may be defined as the ratio of velocity of a charged particle to the potential gradient. It may be expressed in terms of cm/sec per volt/cm.

²See under Pilot Streamer in appendix VII.

draws in the previous concentration of electrons that was bound by the previous positive space charges.

In this manner, breakdown streamers propagate under an adequate potential gradient until the positively charged cloud region is reached. The highly ionized channel left behind by the leader mechanism is of relatively great conductivity compared with neutral air.

Once the intervening space between concentrations of charges has been provided with such a channel, a huge spark may travel along the path blazed by the streamer. This climactic event is brought about by the action of the existing strong potential gradient, for the highly mobile electrons which reside in the nearby negatively charged cloud region are driven at high speed by the gradient along the channel to the positively charged cloud region. The tremendous surge of the electrons ionizes vast numbers of neutral molecules by collision, and creates photons, leading to further ionization, all of which culminates in the development of a brilliant flash of lightning.

By spreading of side branches from the advancing negative leader, a greater volume of the cloud may have its charges neutralized or removed by the stroke.

Counteracting the foregoing processes are the recombination of electrons with positive ions and the attachment of electrons to neutral molecules or aggregates of molecules. These tend to cause decay of the ionization in the channel. If this process goes on sufficiently, the leader may become stepped or cease altogether.

In the case of an airplane of positive polarity with positive streamers from the airplane, electrons are stripped from neutral molecules by impact of a single free electron near the strongest part of the field (presumably at certain extremities of the airplane) and the electron avalanches thus initiated are driven by the field in the direction of the positively charged cloud region, leaving positive ions behind. Photons formed as in the previous case also produce electron avalanches which move in the same direction. Electron avalanches which form near the tip of the positive-ion space charge on the side nearest the negatively charged cloud region move rapidly along the channel of the space charge toward the positively charged cloud region. This phenomenon is very marked, for the positive charges at the tip of the positive streamer on the negative side exert a strong attractive force

for the electrons and facilitate the longitudinal spread of the ionization. Through repeated processes of this sort positive streamers are extended toward the negative side, since the potential gradient there is steepened by the distribution of the charges and the field.

It may be seen from the foregoing that once the highly ionized streamer channel initiated by the airplane bridges the gap between two oppositely charged cloud centers or cloud and precipitation centers, a violent disruptive electrical discharge can take place with the aircraft forming a portion of its path. The discharge will be self-propagating at average potential gradients lower than the critical sparking potential gradient after the initial breakdown occurs. Thus, leaders may propagate from the primary breakdown point and encompass the adjacent cloud or precipitation centers. A strong flow of electrical charges thereby occurs from one of the centers to the other of opposite sign, tending in this manner to produce neutralization.

Without the sufficiently strong potential gradient established between the oppositely charged cloud centers, there could not develop a disruptive discharge. Once the charges in these centers are neutralized and the potential gradient is greatly weakened or nullified, no charges can flow along the ionized channel initially blazed by the streamer, and the discharge must terminate. Owing to the conditions, the disruptive discharge can be expected to have the characteristics of cloud-to-cloud lightning strokes which do not appear to have return strokes as do cloud-to-ground strokes.

Some persons have proposed the following erroneous theory for the origin of the disruptive discharge: (1) The airplane in flying through a highly charged cloud region of one polarity accumulates a heavy charge of like sign; (2) the airplane abruptly enters a highly charged cloud region of opposite polarity; and (3) a disruptive discharge occurs because the charges on the airplane are removed in a form like a spark of static electricity. This concept of the mechanism involved is not supported by the facts, for the capacitance of the airplane is too small to enable the structure to hold enough charge (coulombs) at existing potentials to explain the holes burned by the actual disruptive discharge experienced.

19. RECOMMENDED MAINTENANCE PRACTICES DESIGNED TO PREVENT OR ALLEVIATE POSSIBLE HARMFUL EFFECTS OF DISRUPTIVE DISCHARGES OR STATIC SPARKS

1. Be sure all metallic parts of the structure of the

airplane are well-bonded together. (This lessens both lightning hazards and radio interference.)

2. Where practicable, use a conducting coating and/or a network of well-bonded conducting strips preferably on the outside of important nonconducting, exposed components of the aircraft, especially if such members project appreciably, provided these arrangements do not interfere with the radio or other devices.

3. Be sure that drippings or vapors of fuel or oil are not present where a discharge current may be conveyed into the airplane, as via radio connections or other conductors insulated from the body of the airplane, and nonconducting exposed members (like plastic nose compartments or blisters).

4. Owing to danger of an explosion from static sparks, the aircraft structure should invariably be grounded when refueling. To avert the possibility of airport personnel receiving a severe shock from static electricity, it should also be grounded as soon as possible after landing.

20. RECOMMENDED FLIGHT PROCEDURE TO AVOID DISCHARGES AND ALLEVIATE HARMFUL EFFECTS

The following flight procedure, based on the facts presented in the preceding sections of this report, is recommended to pilots as a means of reducing the chances of experiencing a disruptive electrical discharge to aircraft, and of alleviating any resultant harmful effects if a discharge takes place:

1. Avoid flight through large or towering cumulus and cumulo-nimbus clouds, especially at levels where the temperature is from 20° to 40° F. (The layer with temperatures between about 24° and 40° F, i.e., $32^{\circ} \pm 8^{\circ}$ F, is most frequently the scene of discharges.)

2. Avoid flight through cumulo-nimbus clouds, at levels where the temperature is between $+15^{\circ}$ and -10° F, for high potential gradients and consequently disruptive discharges can be expected. (In addition, ice crystals, snow, sleet, or hail usually will be encountered under such conditions. The hail may produce serious damage.)

3. Avoid flight in the immediate vicinity of cumulo-nimbus clouds, especially when they have given manifestations of thunderstorm activity. It is preferable to keep at least 2500 feet or more away from them.

4. Avoid flight through moderate or heavy rain and/or snow, sleet, hail, or ice crystals, especially at levels where the temperature is from 20° to 40° F, particularly if the precipitation is from cumuliiform clouds.

5. If the precipitation static and/or corona discharge (St. Elmo's fire) is moderate to severe, and there is evidence from the temperature, cloud, and precipitation conditions that the airplane is in a zone of strong potential gradient between oppositely charged regions, reduce speed somewhat (see sec. 21, par. 7) and seek a lower level where temperatures above 40° F prevail, or leave the given cloud and precipitation conditions. Tendency for coronal streamers to build out rapidly and for precipitation static sounds to increase rapidly in intensity should be regarded as precursory signs that a discharge is imminent. (Reduction in speed allows acquired charges to diminish and permits the corona discharges to lessen in intensity. It also is possible that these results prevent the potential gradient at the airplane from building up to such extreme values as otherwise would be attained.)

6. If existing conditions are favorable for a discharge and the signs are present that a discharge may be imminent, be sure that the antenna is grounded. In flight through meteorological conditions wherein a discharge might be expected, have the trailing antenna reeled in, if such is used on the aircraft.

7. If the signs are present that a discharge may be imminent, or that a discharge might be expected under existing conditions, have the cockpit lights turned up full bright. Also, keep the eyes focused on the instrument panel, especially at night, as this will alleviate temporary blindness resulting from a lightning discharge to the aircraft. One of the pilots, at least, should shield his eyes by holding his head down in the cockpit, keeping his eyes closed or focused on the brightly lighted instrument panel. Opaque goggles may be worn in lieu of this, or opaque curtains may be drawn to shield one or both pilots when flight on instruments is not objectionable for other reasons. Another suggested protective measure is the wearing of a long visor which shields the eyes from any lightning flash that might be seen through the windshield or the side windows, but allows the pilot to observe his cockpit instruments. Still another suggestion, having the same object, is the wearing of goggles the upper portion of which is rendered opaque and the lower portion kept transparent. Sun goggles may be worn in the daytime as a partial protective measure for vision during flight under thunderstorm conditions.

8. If the automatic pilot is not already engaged, have it ready to engage immediately if a discharge occurs.

NOTE: One authority has stated in regard to this matter:

"While it is not general practice, it is considered good policy in flying through either turbulent air or in regions of possible electrical discharge to have the automatic pilot engaged but with the servo control turned down so the pilot's control can override the mechanical control. With such an adjustment the pilot retains his manual control at all times, but if necessary can give full control to the automatic pilot by turning up the servo unit. This method also eliminates the possibility of the automatic pilot placing undue strain on the controls under severe turbulent conditions that would bring about * * * * * stalling and structural strain,"

which it is desirable to avoid.

9. If the signs are present that a discharge may be imminent, or that a discharge might be expected under existing conditions, do not hold the radio earphones too close to the ears. This will tend to prevent acoustic shock. Strong lightning crash static (atmospherics) may be regarded as a sure sign of nearby thunderstorm conditions, even though lightning is not observed because of poor visibility.

10. When landing after a flight in which the aircraft acquired a strong electrical charge, an electrical conductor forming part of, or connected with, the metallic structure of the aircraft should be caused to make contact with the ground or the water in order to discharge the static charge from the aircraft, before any person makes the contact. (The use of trailing wire or other discharge devices during flight immediately prior to landing may obviate the need for any special discharge conductor such as that implied above.)

AN EXAMPLE OF PROCEDURE WHICH APPARENTLY PREVENTED

A DISCHARGE TO THE AIRCRAFT

There follows a copy of a report rendered by an air line pilot which illustrates how certain precautionary measures

taken when a discharge seemed imminent apparently prevented an electric breakdown from occurring:

"At 11,000 feet, flying east of "A,"¹ a constant temperature at 38° F was observed until the flight reached the vicinity of "B," where the temperature gradually lowered to 35° F. In the vicinity of "C" light snow was encountered while on instruments and the temperature lowered abruptly to 32° F. Static increased steadily between "C" and "D," blocking out all radio reception and at this time some St. Elmo's fire was observed on the propellers.

"At about "D" the static reached a maximum of intensity, the snow changed from a pure crystalline to a more liquid state, sticking to the windshield, while the temperature dropped to 25° F momentarily. The corona on the propellers increased in intensity, estimated 12 inches long. The nose of the ship then went into corona discharge, long flamelike discharges extending forward quite some distance, apparently about 20 feet.

"Anticipating a sudden discharge, the throttles were closed to reduce forward speed and a descent was started. The corona on the nose immediately ceased as the throttles were closed and descent begun.

"On reaching 9000 feet, power was increased to normal and descent checked. The temperature was 38° F at this level, snow had changed to rain with little static and no corona discharge.

"If the same speed and level of flight had been maintained at 11,000 feet it is believed the ship would have been struck by lightning, since immediately after lowering below the cloud deck a severe discharge of lightning occurred close to the left wing."

¹The letters "A," "B," "C," and "D" are intended to designate certain specific cities or towns in the vicinity of the airway over which flight was made.

21. RECOMMENDED FLIGHT PROCEDURE AND PRECAUTIONS TO AVOID OR
ALLEVIATE HARMFUL EFFECTS FROM SEVERE METEOROLOGICAL
CONDITIONS (OTHER THAN DISRUPTIVE DISCHARGES)
ASSOCIATED WITH THUNDERSTORMS

1. If the precipitation intensity or the concentration of moisture in the clouds seems to be relatively great, as evidenced by unusual wetness, have the carburetor preheat full on. This probably will tend to prevent rough engine action or engine stoppage.

2. Avoid instrument flight in areas where towering, tropical cumulus clouds may be encountered. The severe turbulence therein offers serious hazards for night flying.

3. Avoid the turbulent zones within growing or active cumulo-nimbus clouds, especially where the rapidly ascending core and the surrounding descending exterior adjoin. Other turbulent zones to be avoided are near the narrowed portion of the core in the vicinity of the freezing level and above that wherever the buoyancy of the updrafts are rapidly diminishing. Accelerations of considerable magnitude may be encountered, capable of doing structural damage to the aircraft in some cases.

4. Avoid the downdrafts in the neighborhood of the base of active cumulo-nimbus clouds and their accompanying squall clouds. Also, avoid the downdrafts associated with heavy rain (usually cold) which descends in gushes from cumulo-nimbus clouds. Rapidly dissipating cumulo-nimbus clouds, too, are characterized by strong downdrafts at almost all levels, and these must be avoided.

5. Avoid flight through or in the immediate vicinity of line squalls and especially of the attendant roll cloud, for there is danger of encountering violent turbulence which renders an aircraft unmaneuverable or is likely to do structural damage. Avoid a path intended to effect flight underneath an approaching squall cloud or heavy shower, as downdrafts may induce dangerous, diving angle of attack and accelerated descent, wherein pull-out may not be possible before the surface is reached. Flight below or within regions of downdrafts which may carry an aircraft to the surface is therefore especially fraught with danger. Overrunning cold fronts and pre-frontal line squalls have especially great hazards associated

with them. Tornadoes and hail appear to occur most frequently in conjunction with the prefrontal type.

6. It is preferable to avoid flight through or beneath cold-front and orographically produced cumulo-nimbus clouds and thunderstorms, as adverse conditions of unusual severity may be expected, particularly if the warm air mass involved is very moist and is, or can readily become, conditionally unstable by lifting. (Tropical maritime air masses have these characteristics most often.) Downdrafts, torrential rain gushes, turbulence, ice accretion, and hail associated with storms over mountainous terrain where peaks may be wholly obscured by clouds present most extreme combinations of hazards.

7. If flight must be made through a thunderstorm, it is generally preferable to fly at somewhat reduced speed (see note below) in the region a small to moderate distance above the top of the roll cloud and just above the accompanying strato-cumulus cloud deck. Inasmuch as turbulence usually increases with height at the boundaries of the rising core of air, less turbulence can be expected in this region.

NOTE : Too great a reduction of speed is highly objectionable since reduction of speed may lead to stalling and loss of control, which is especially dangerous in turbulent air. It is therefore desirable to remain at a safe speed above the stalling speed. One authority has suggested that the rough-air operating speed should be placed midway between the stall speed, flaps up, and the design maximum speed for level flight, with both figures based on the normal gross load condition. Some authorities consider the desirable method of reducing speed is to lower the landing gear. There are objections to reducing speed by reducing engine power alone, for there is a risk of inducing the formation of carburetor ice or of fouling the spark plugs, with the undesirable result of insufficient power being available when and if needed.

8. Avoid flight through the "light spots" or "greenish hued" regions in an active thunderstorm, as these are considered to be regions of severe turbulence and hail. (Light spots are regions where the cloud mass has a consistent filmy white texture and lacks the "boiling" contour of cumulus clouds. There is reason to believe that such regions are spaces where ice particles falling into concentrations of water particles cause rapid condensation, and possibly hail. Strong air currents also may be produced.)

9. In flying in the vicinity of a line of thunderstorms, it is preferable to maintain flight under clear sky or under high overcast, rather than beneath an intermediate overcast cloud layer. (The reason for this is that thunderstorms have a tendency to build out above the strato-cumulus, alto-cumulus, or alto-stratus layer and suddenly release heavy rain or hail in advance of the squall cloud. These are attended by moderate to severe turbulence.)

10. Possibility of encountering hail on the leeward side of the thunderstorms that are "skirted" too closely suggests that the immediate neighborhood should be avoided for that reason as well as for the reason that cloud-to-air lightning strokes might involve the aircraft.

11. If flight below a thunderstorm must be made because the storm cannot be flown over or detoured in the clear, be certain there is adequate clearance (at least 2000 ft) between the cloud base and the aircraft, as well as between the aircraft and the ground (preferably not less than 4000 ft). The heavy rain curtain, the roll clouds near the cloud base, and the region of strong updrafts and downdrafts should be especially avoided. Thunderstorms which are several hours old and are diminishing in intensity can be more safely flown under than young and vigorous thunderstorms.

12. Avoid flight at low levels between two neighboring thunderstorms, especially if the storms are "young" and energetic. The strong descending currents in this area, engendered by the combined effects of the two disturbances, frequently manifest and produce extreme turbulence of hazardous proportions.

22. RECOMMENDED PROCEDURE IN THE EVENT OF MAGNETIC COMPASS FAILURE IN FLIGHT

In a small number of cases electrical discharges appear to demagnetize magnetic compasses, and in other instances the compasses become unreliable as the result of magnetism induced in the steel structural framework of the aircraft by the heavy discharge current. The succeeding instructions, which describe steps designed to alleviate the deficiency in such cases, are taken from a General Information Letter of

May 2, 1938, forwarded by Transcontinental and Western Air, Inc., to all its flying personnel on the subject:¹

"In the event of magnetic compass failure in flight, it is recommended that the following procedure be adopted, so that the pilot may orientate himself and establish direction.

"If completely lost on instruments, due to compass failure, it then becomes necessary to make use of both the directional gyro and the direction finding equipment aboard the airplane.

"Orientation under these conditions may be accomplished as follows:

1. Tune in a station, preferably one which lies on the route within reasonable distance limits, and one from which a clearly audible signal may be received.
2. Solve orientation problem and home.
3. If the ceiling is such that a landing cannot be effected - immediately tune to some other station within a reasonable distance which gives a clear signal and home accordingly. The initial homing heading toward the second station will be the bearing of the second station from the first and therefore provides a directional heading on which to set the gyro.

If the ceiling of the second station is such that a landing cannot be effected, direction will at least be established so that the pilot may head toward an area suitable for landing.

Precautionary Measures

1. In solving the orientation problem for the initial station it will probably be necessary to fly for three to six minutes on the 90 degree leg (at right angles to homing course) in order to get a sufficient change in null progression, since the plane may be considerably distant from the station.

¹Appreciation is due the Transcontinental and Western Air, Inc., for kindly furnishing the instructions for use in this publication.

It will also be essential to hold as steady a course as possible whenever setting the gyro to null or when establishing null progression.

2. During the homing procedure on the initial station the first officer should choose another station giving consideration to distance and also source of signal strength and should observe or measure the bearing of the second station from the first, since this will be the bearing of alignment on which to set the gyro when over the initial station. Be careful not to use the reciprocal.
3. Care should be exercised when solving the orientation problem on the second station; and if it is found that the plane was heading away from the station then the gyro should be changed by 180 degrees.
4. When possible, in normal flight, make it a practice of checking the rate of precession on the directional gyro so that it can be set accordingly on a time basis.
5. Prior to flying into an area where St. Elmo's fire is prevalent, carefully check the gyro against the magnetic compass and it is recommended that you do not change the gyro until such time as the condition has been passed, providing the condition flown thru is not too extensive. If the procedure outlined in Paragraph 4 has been followed, it is possible to reset the gyro on a time basis due to the fact that the magnetic compass may be strongly affected as a result of St. Elmo's fire.

*** *** ***

The following procedures are of practical value and may be adopted providing the pilot can climb up thru the overcast and break out on top.

Night Time

Direction may be established by locating the North, or Pole Star and aligning the direction of the flight toward it. This direction is True North. To obtain magnetic equivalent

subtract the variation of your locality from 360 degrees for Easterly variation and set the directional gyro accordingly. Conversely, if the variation is Westerly add variation of locality to zero and set the gyro.

Day Time

Direction may be established, plus or minus 20 degrees by setting one's watch to the established time zone of the locality in which the plane is flying and pointing the hour hand of the watch toward the sun. True South will be indicated by a point midway between the hour hand and the figure "12", using, of course, the shorter of the two arcs, i.e. South may be found by bisecting the angle between the hour hand and the figure 12."

23. ENGINEERING DATA

Data of interest to aeronautical engineers in connection with the possible effects of disruptive electrical discharges upon certain aircraft structures are given in appendix II of this report. Temperature and altitude data for the occasions of such discharges are given in appendix III on the basis of available information. These data are useful in determining whether aviation fuels and lubricants are inside or outside of their inflammability limits under the given conditions.

With regard to magnetic effects of lightning it may be recalled (see sec. 15) that there are a few cases on record where it was claimed that the permanent magnets of the magnetos may have been influenced or that the magnetic compass was affected, either by demagnetization or by magnetization of some nearby steel parts of the aircraft. For information as to the shielding of permanent magnets from transient magnetic fields, the interested reader is referred to an article regarding that subject by Wey (reference 16). For information as to means of eliminating or correcting airplane magnetization, the reader may consult an article by Lee (reference 17).

U. S. Weather Bureau,
Washington, D. C., April 1945.

APPENDIX I

BRIEF GLOSSARY OF SOME IMPORTANT METEOROLOGICAL TERMS

The following brief glossary is included for the benefit of the nonmeteorological reader. It is confined largely to terms relating to the thermodynamics of the atmosphere essential to understand in connection with the discussion in section 10 and appendix V. The arrangement is such as to provide a more-or-less logical development of the subject if the definitions and the discussions are read consecutively.

1. Lapse rate - the rate of decrease of temperature with height in the atmosphere

2. Dry-adiabatic lapse rate - a rate of decrease of temperature with height approximately equal to 1°C per 100 meters (0.55°F per 100 ft). This is close to the rate at which an ascending body of unsaturated air will cool due to adiabatic expansion. The lower pressure encountered during ascent permits expansion, hence cooling. Higher pressure encountered during descent causes compression, hence heating.

3. Adiabatic process - a process during which no heat is communicated to or withdrawn from the body or system concerned. An example of an adiabatic process is the change of temperature and pressure within a parcel of air undergoing ascent or descent in the atmosphere rapidly enough so that the surrounding air has little opportunity to transfer heat to the parcel or vice versa. The work done by an ascending parcel in expanding against the surrounding air uses some of the heat energy of the air in the parcel, thus causing cooling of the parcel. The reverse is true in regard to a descending parcel.

4. Saturated-adiabatic lapse rate - a rate of decrease of temperature with height equal to the rate at which an ascending body of saturated air will cool during adiabatic expansion, where all the products of condensation are carried along by the moving body of air. The saturated-adiabatic lapse rate is not constant as in the case of the dry-adiabatic lapse rate but varies with temperature, pressure, and original moisture content of the air. It is always less than the dry-adiabatic lapse rate, and increases as the temperature decreases. (An approximate average value for the saturated-adiabatic lapse rate is 0.6°C per 100 m.) Saturated-adiabatic lapse rate also is called wet-adiabatic lapse rate and moist-adiabatic lapse rate.

5. Pseudoadiabatic lapse rate - a rate of decrease of temperature with height equal to the rate at which an ascending body of saturated air will cool during an expansion which is adiabatic, except that all products of condensation fall out of the body of ascending air as rapidly as formed. For practical purposes the value of the pseudoadiabatic lapse rate may be regarded as substantially equal to the saturated-adiabatic lapse rate under the same conditions of temperature, pressure, and original moisture content of the air. Forced descent of air which has undergone pseudoadiabatic ascent immediately causes it to become unsaturated and to warm up at the dry adiabatic rate; since products of condensation, having fallen out, are unavailable to maintain the air in a saturated condition.

6. Stability - a state in which the vertical distribution of temperature is such that a parcel of air will resist either upward or downward displacement from its level by a disturbing force. The resistance in the case of upward displacement is due to the fact that the parcel is colder than the surrounding air, therefore denser; hence it sinks back to its original level when the disturbing force ceases to act. The resistance in the case of downward displacement is due to the fact that the parcel is warmer than the surrounding air, therefore less dense; hence buoyancy causes it to rise to its original level when the disturbing force ceases to act.

7. Stability of unsaturated air - Unsaturated air is stable as long as the existing lapse rate is less than the dry-adiabatic lapse rate.

8. Stability of saturated air - Saturated air is stable as long as the existing lapse rate is less than the saturated-adiabatic or pseudoadiabatic lapse rate.

9. Instability - a state in which the vertical distribution of temperature is such that a parcel of air, if given either an upward or a downward impulse, will tend to move away with increasing speed from its original level. The force causing the parcel to continue in upward motion after an initial upward impulse is buoyancy resulting from the parcel's being warmer than the surrounding air, hence less dense (lighter). The parcel continues in downward motion after an initial downward impulse because it is colder than the surrounding air, hence more dense (heavier).

10. Instability of unsaturated air - Unsaturated air is unstable when the existing lapse rate is greater than the dry-adiabatic lapse rate.

11. Instability of saturated air - Saturated air is unstable in the upward direction when the existing lapse rate is greater than the saturated-adiabatic or pseudoadiabatic lapse rate. Downward displacement of saturated air causes its temperature to increase, which leads to evaporation of the contained liquid water, snow, or ice crystals, and eventually to an unsaturated state when the latter are entirely evaporated and/or removed by falling out.

12. Conditional instability - a state in which the vertical distribution of temperature is such within a layer of atmosphere that stability for unsaturated air prevails but instability of saturated air would occur if saturated air were introduced at the base of, or anywhere else within, the layer. Conditional instability obtains whenever the existing lapse rate within the layer exceeds the saturated-adiabatic or pseudoadiabatic lapse rate, but is less than the dry-adiabatic lapse rate.

13. Absolute stability - a state in which the vertical distribution of temperature is such within a layer of atmosphere that stability for saturated air would prevail in the layer if saturated air were introduced anywhere within it. This also implies stability for unsaturated air. Absolute stability obtains whenever the existing lapse rate within the layer is less than the saturated-adiabatic or pseudoadiabatic lapse rate.

14. Convective instability - Apart from the case where a layer already is unstable for saturated air and has saturated air present in its lower portion, at least, convective instability implies one of the following possibilities:

- (a) If a layer of air currently has a lapse rate which is stable for saturated air, and has saturated air present in its lower portion, sufficient lifting of the layer as a whole eventually will cause the layer to become conditionally unstable while saturated air is present in its lower portion.
- (b) If a layer of air currently has unsaturated air in its lower portion, a certain amount of lifting of the layer as a whole will cause the lower portion to become saturated with the layer stable for saturated air, but sufficient additional lifting eventually will cause the layer to become conditionally unstable with saturated air present at its base.

- (c) If a layer of air currently has a lapse rate which is either stable or unstable for saturated air and has unsaturated air in its lower portion, sufficient lifting of the layer as a whole will cause the base to become saturated while the layer is conditionally unstable.

Summarizing: Convective instability of a layer of air implies that, if it is not already conditionally unstable with saturated air present in its lower portion, then it can be brought to that state by sufficient lifting. When that state is reached, the instability of the layer for saturated air is manifested by the actual (thermal) convection of saturated air from the lower portion to its upper portion or higher, with consequent increase in the vertical development of the clouds formed by products of condensation, and the occurrence of turbulent currents caused by the convection.

15. Convective stability of a layer of air implies that it is currently not unstable for saturated air with saturated air present in its lower portion, and that, moreover, the layer cannot be brought to a state of conditional instability with saturated air present in its lower portion despite any amount of lifting. A layer which is convectively stable therefore cannot actually exhibit instability for saturated air by any adiabatic process which the layer may undergo as a whole.

16. Convection - the upward or downward movement, mechanically or thermally produced, of a limited portion of the atmosphere. Mechanical or forced convection is due to displacement of the body of air upward or downward by an external disturbing factor which forces the air from its original level, as when horizontally flowing air strikes an obstacle like a hill and is forced to flow over it. Thermal convection is active when an upward-impelled parcel of air is warmer, hence less dense, than its surroundings and continues to ascend as long as it thus possesses buoyancy; while, on the contrary, the opposite (i.e., sinking) effect is produced when a downward-impelled parcel of air is colder, hence more dense, than its surroundings and continues to descend as long as it thus remains heavier than an equal volume of surrounding air. Thermal convection readily occurs in unsaturated air when the existing lapse rate exceeds the dry-adiabatic lapse rate, and in saturated air when the existing lapse rate exceeds the saturated-adiabatic or pseudoadiabatic lapse rate. (See Instability.) The approximate upper limit of thermal convection is the level where the temperature of the ascending

parcel of air just begins to be less than that of the surrounding air, although if the parcel has considerable upward momentum when it reaches this level it will overshoot. A parcel of air undergoing upward convection cools by expansion approximately in accordance with the dry-adiabatic lapse rate if it is unsaturated, and with the pseudoadiabatic lapse rate if saturated.

APPENDIX II

LABORATORY TESTS ON EFFECTS OF "ARTIFICIAL" LIGHTNING UPON SHEET METAL AND WINDSHIELD GLASS

The High Voltage laboratory of the General Electric Company at Pittsfield, Mass., under the direction of Dr. K. B. McEachron, and the corresponding laboratory of the Westinghouse Electric and Manufacturing Company at Sharon, Pa., under the direction of Mr. P. L. Bellaschi have conducted valuable experiments for the NACA in an effort to discover the effects of simulated lightning discharges upon certain exterior portions of the modern aircraft structure.

The results of these tests are briefly summarized here.

1. GENERAL ELECTRIC COMPANY LONG-DURATION LOW-CURRENT TESTS ON SHEET METAL

Tests were made on sheets of metal of various kinds and thickness with low-current electric arcs in order to determine the relationship between the area of the hole burned in the sheets and the thickness of the metal in addition to the total quantity of electrical charge that flowed through the arc. The low-current arcs used were intended to simulate the low-current continuous component at the tail end of lightning strokes (see appendix VII - Subheading: "Effects of Component Parts of Return Stroke") and the continuous low-current type of lightning discharges which are sometimes encountered by aircraft. The test arcs were initiated by a low-current negative polarity impulse followed by a negative direct current power current ranging from 80 to 500 amperes. This method was found to produce burns most nearly like those made by actual

lightning strokes of the continuous, long-duration, low-current type.

Electrodes were generally separated by a gap of 1/4 to 1/2 inch from the sheet under investigation. In the tests on copper, changing the size of the gap between electrode and sheet from 1/8 to 1/4 to 3/8 inch did not seem to produce any material difference in results.

The data secured on copper sheets, aluminum sheets, and stainless steel (from Fleetwings, Inc.) are of especial interest.

The results may be summarized in the following two equations which relate the essential quantities involved:

For sheets of copper, aluminum, and stainless steel (from Fleetwings, Inc.)

1. Having a thickness of 0. to 35 mils:

$$A_1 = 25.3 C t^{-0.9}$$

and

2. Having a thickness of 35 to 150 mils:

$$A_2 = 245 C t^{-1.54}$$

where

A area of hole burned by arc, square millimeters

C quantity of electric charge through arc, coulombs

t thickness of sheet, mils

These equations apply equally well with good approximation to copper, stainless steel, and aluminum.

It may be noted that the average number of coulombs measured in natural lightning strokes is 20 to 35, while the maximum ever measured was slightly greater than 300.

The following data present some typical results for the sake of illustration:

Type of sheet metal (Plain, except * = seamed)	Thickness of metal (in.)	Shape of electrode	Direct current (amp)	Arc duration (sec)	Coulombs through arc	Hole area (mm ²)	Largest area of melted top surface (mm ²)
Copper	0.020	Pointed	81	0.521	27.2	45	-----
Do-----	.020	---do---	495	.123	52	127	-----
Aluminum	.025	Blunt	426	.107	75	132	285
Do-----	.025	---do---	436	-----	144	264	497
Do-----	.025	Pointed	85	.248	22.4	20	117
Do-----	.051	Blunt	426	.202	115	93	208
Do-----	.051	---do---	446	.55	242	155	378
Do-----	.100	---do---	446	.482	203	40	222
Do-----	.100	---do---	446	.525	232	76	191
Stainless steel	.010	Pointed	91	.075	7.2	16	-----
Do-----	.010	---do---	81	.160	14.3	51	-----
Do-----	.010	Blunt	716	.167	111	315	-----
Do-----	.040	---do---	115	.798	92	60	-----
Do-----	.040	---do---	775	.167	117	86	-----
*Do-----	.010	---do---	475	.312	140	216	-----
*Do-----	.020	---do---	700	.217	142	110	-----

*Spot-welded, seamed sheets of indicated thickness overlapped 1/2 in.

Electrodes were of hard, 1/4-inch carbon rods, either blunt as indicated, or sharpened to a point similar to that on a sharp lead pencil, but with more taper.

The type of hole burned in the aluminum appears to be different from the one burned in the plain copper. There is a definite melted area surrounding the actual hole in the aluminum which is not found to any extent in the copper. The last column of the foregoing table represents the area of hole burned through by the arc plus the surrounded melted area of metal. Holes were burned more readily in the aluminum than in the copper, especially for thicker sheets. As the thickness increases, the holes are not burned straight through in cylindrical form but are tapered.

Double-Wall Tests on Stainless Steel

Tests were made on low-current arcs to double sheets of stainless steel to simulate the condition of lightning strokes to double-wall gasoline tanks in airplanes. Different conditions of circuit, grounds, sheet separation, and sheet thickness were tried at substantially constant charges in the arc (about 100 to 120 coulombs). The sheets were held in a vertical position, separated by wooden spacers, with the electrode in a horizontal plane (perpendicular to the sheets). The tests appear to indicate that gas tanks with the outer wall grounded and the inner wall isolated would afford the best protection and those with both walls grounded are almost as good. To insure that the holes are not burned in the inner wall, the spacing between inner and outer wall for 16-mil sheet stainless steel (as per sample from Fleetwings, Inc.) must be over 1 1/2 inches; for 20-mil, it must be 3/4 inch or more; for 30-mil, it must be 3/8 inch or more; and for 40-mil, it must be 1/4 inch or more. In order to assure safety of fuel tanks, therefore, rather liberal spacing in double-wall tanks should be used. Holes burned in the sheet nearest the electrode, when that sheet is isolated while the sheet farthest from the electrode is grounded, have about a 70- to 80-percent smaller area than when the first sheet conducts the current to ground directly.

Designating the sheet nearest the electrode as No. 1, and the other as No. 2, the following table shows a compilation of the test data indicating the relationships between thickness of metal, grounding or isolation of metal, spacing between sheets, areas of holes burned in the respective sheets, and the coulombs conveyed through the arc:

Double Wall Construction of Stainless Steel Sheets

Thickness of sheet (mils)	Grounded sheet	Isolated sheet	Spacing between sheets (in.)	Hole area sheet 1 (mm ²)	Hole area sheet 2 (mm ²)	Coulombs
16	1	2	0.5	157	84	104
16	1	2	.75	160	80	110
16	1	2	1.00	155	50	108
16	2	1	.25	104	178	115
16	2	1	.375	109	204	122
16	2	1	.500	118	190	113
16	1 and 2	-----	1.00	141	72	116
16	1 and 2	-----	1.25	148	33	106
20	1	2	.5	145	50	112
20	1	2	.75	123	62	106
20	2	1	.5	100	152	104
20	1 and 2	-----	.5	109	76	>110
20	1 and 2	-----	.75	106	196	>110
30	1	2	.25	103	172	108
30	2	1	.25	81	76	109
30	1 and 2	-----	.25	85	142	109
40	1	2	.5	105	10	103
40	1	2	.25	77	137	118
40	2	1	.5	74	0	99
40	1 and 2	-----	.5	74	0	112
40	1 and 2	-----	.25	70	120	112

¹Area of burn - no hole formed.

Inasmuch as actual lightning strokes have been measured to attain a maximum value of at least 300 coulombs, the tests based on 99 to 122 coulombs do not show the most severe conditions that must be provided against. Therefore, spacing allowances considerably greater than the maximums shown in the table would be required to provide safeguard against the maximum intensity of lightning stroke that might possibly be experienced.

Tests on Aluminum Tubing

Tests were made on aluminum tubing of 0.025-inch wall thickness and 1 inch in diameter from an airplane rudder bow.

A general idea of the results of these tests on aluminum tubing may be gained from the following table:

Direct current (amp)	Arc duration (sec)	Coulombs	Hole area, top ¹ (mm ²)	Hole area, bottom (mm ²)	Extra hole burned, area (mm ²)
-----	-----	13.5	² 12.5	None	None
223	0.195	40	38	None	None
193	0.188	35	² 78	² 71	None
436	.278	113	155	39	65

¹Side of tubing nearest electrode

²Area of burn

There appear to be two correlations between coulombs and top hole area: one where the hole or burn occurred only on one side of the tube (nearest electrode), and another where holes or definite burns (melted areas) occurred on both sides of the tube.

Holes of known size burned in three similar tubes by actual lightning strokes apparently were caused by strokes which passed 8, 38, and 110 coulombs, judging from laboratory-

derived relationships connecting burn hole area and coulombs.

Tests on Steel Plate

An attempt was made to burn a hole in 3/8-inch steel plate, but it was found that the limitations of the circuits prevented this. Also, the coulombs required would be much greater than the charge of any lightning stroke ever recorded. In the test, a 420-coulomb arc could not burn a hole through the plate, but a craterlike hole 0.188 inch deep from the (blunt) electrode side was produced, and the largest area of melted top surface was 180 square millimeters. Thermocouple measurements of the maximum temperature reached at a point on the side of the plate just opposite the burn were only 80° to 85° C.

2. WESTINGHOUSE ELECTRIC AND MANUFACTURING

COMPANY TESTS ON SHEET METAL

Long-Duration, Low-Current Tests

Investigations were conducted by Bellaschi (reference 6), on effects of long-duration, low-current arcs on sheets and rods. The test apparatus consisted of an impulse generator which initiates the breakdown of the air gap between the high-voltage terminal and the aluminum sheet tested. Sixty-cycle current, supplied from a high-voltage power transformer, followed. A copper rod machined to conical form, with height equal to rod diameter, was used as one of the electrodes. The aluminum sheet was grounded. The arc was between the tip of the rod and the face of the sheet.

Some representative results of these tests are shown in the following table:

SIXTY-CYCLE CURRENT FUSION TESTS

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Sample	Diameter of copper rod or wire (in.)	Thickness of aluminum sheet (in.)	Current (amperes) (root mean square)	Arc duration (cycles) (of 60-cycle current)	Charge (coulombs)	Fusion effects	Volume of copper fused (mm ³)	Volume of aluminum fused (mm ³)	Coulombs per mm ³ of aluminum fused
B	0.20	0.020	3500	1/2	26.2	Wire tip fused 1/8 in.; 1/4 in. hole burned in sheet	8.6	16.2	1.62
D	0.20	0.030	500	8 1/2	63.8	Entire wire tip fused; 1/2 in. hole burned in sheet	34.4	97	0.66
F	1/4	0.020	1350	8 1/2	172	Tip plus 1/16 in. rod fused; 1 1/2 in. hole burned in sheet	118	580	0.30
I	1/2	0.035	1200	8	144	Rod tip fused 1/4 in.; 1 1/4 in. hole burned in sheet	67.6	510	0.28
K	1/4	0.095	1300	8	156	Tip plus 1/32 in. rod fused; 1/2 in. crater in sheet	93	-----	-----

Note: The polarity of the rod or wire on the first half-cycle is positive for the tests on samples B, D, F, and negative on samples I and K.

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There appears to be a fairly constant value of coulombs per cubic millimeter of aluminum fused in the range of test conditions illustrated by the data for samples F and I. The range of the value in question was from 0.28 to 0.33 under these conditions.

Short-Time, High-Current Tests

These tests, similar in arrangements to those outlined above, involved a high-current impulse instead of 60-cycle current. Typical results of these tests are indicated by the following data:

Sample S 18: 1/4-inch diameter copper rod; 0.035 inch aluminum sheet; crest current = 17,000 amperes; duration of arc = 0.0045 second; charge = 23 coulombs; fusion effects: rod fused 0.195 inch. Tip of rod blasted. 1/4 inch crater fused on sheet and splashed out.

Sample H.S.: 1/4-inch diameter copper rod; 0.035-inch aluminum sheet; crest current = 125,000 amperes; duration of arc = 0.0004 second; charge = 15 coulombs; fusion effects; rod blistered heavily at tip, no concentration of fusion. Discharge blasted up rod 1.5 inch. Fusion on sheet concentrated in 5/8-inch diameter (core of current discharge), to estimated depth of 0.005 to 0.010 inch. Metal fused approximately 25 to 50 cubic millimeters. Fused metal in 7/8-inch cusp form extending from core indicated molten metal was sucked up during discharge and deposited back on sheet. Sheath of discharge blasted out several inches from core.

It will be noted that the "burning" effect produced on metals by the high current component of lightning strokes is confined to a thin top layer at the surface of the metal. The duration of the initial high current in lightning discharges is relatively short, not more than 200 millionths of a second. For such currents, the average current density at the metal surface in contact with the arc is from 300 to 1000 amperes, depending somewhat on the metal and the polarity. Therefore the surface of metals is merely marked or blistered by the high current.

3. PURDUE UNIVERSITY TESTS ON WINDSHIELDS UNDER SPONSORSHIP OF UNITED AIR LINES

The United Air Lines made arrangements under which the Engineering Division, Engineering Experiment Station, of Purdue University conducted experiments of glass breakage by adjacent lightning discharges. Of tests made on two 8- by 10-inch samples of "Aerolite" Safety Glass 0.142 inch and 0.148 inch in thickness mounted rigidly in a heavy wooden frame, it was found that the rear glass fractured with a single fracture in one case, and with cracks in the other case. In both of these tests a heavy surge of current was caused to flow through an 8½-inch length of No. 32 copper wire placed in contact with the front surface of the glass. The short circuit current of the generator was 65,000 amperes. The initial discharge vaporized the wire and supplied an ionized path for the remaining discharge along the surface of the glass. The fractures (on the side away from the arc) were parallel to the wire and seemed to be the result of concussion due to the pressure and expansion associated with the arc. Evidence was also obtained that the concussion is sufficiently sudden to make possible traveling waves in the glass, although the effect of these is largely determined by the method of mounting and the size of the sample.

These tests are not wholly conclusive inasmuch as the thickness of the glass which formed the working samples was not so great as that of normal aircraft windshield glass. In addition, the possible effect of aerodynamically produced pressure differences between the two faces of the glass was not taken into account, although it is understood that the differences in the case of a typical transport airplane are relatively small (for the Douglas DC-3 they are of the order of 1 psi).

4. GENERAL ELECTRIC COMPANY TESTS ON WINDSHIELDS

Tests were conducted at the High Voltage laboratories of the General Electric Company at Pittsfield, Mass., under the direction of Dr. K. B. McEachron.

The Douglas Aircraft Company kindly cooperated by supplying a cockpit assembly, complete with windshield, for the experiments. A high potential electrical discharge was induced

between the gaps of electrodes in the vicinity of double strength window glass. The preliminary estimates of the potential difference involved across the gaps were in the neighborhood of 150,000 volts. (With regard to the current strength used in these tests, the minimum number of kilo-amperes required to crack 1/4-inch thick safety glass was of the order of magnitude of 80, but the glass did not break through in these cases. The maximum crest current used in an oscillatory arc with 21 microsecond period was 235,000 amperes in one case.) An inspection of the sample glass after the discharge rendered it unsuitable for further use. The surface of the glass exposed to the electrical discharge had taken on a sand-blast appearance. This condition was confined to a surface layer perhaps one to two thousandths of an inch in thickness. Over some portions of this exposed surface a thin film of glass approximately three to four thousandths of an inch in thickness had been completely lifted from the main body of the material. Both the sand-blasted and the thin glass film had a clear appearance rather than a white fused appearance as might be expected from an application of high heat to glass material.

A second test was made using shatterproof glass 1/4 inch thick. After these were subjected to several electrical discharges, it was found that they were considerably cracked in a small, weblike pattern, although the glass held together. Each discharge distorted the glass pane in a cup-shaped manner extruded to the extent of roughly 1/8 inch at its center portion.

A third test was made by inducing a high potential discharge in the vicinity of a movable front sliding section taken from a Douglas DC-3 cockpit windshield enclosure. The discharge caused a failure similar to that of the specimens of shatterproof glass mentioned under the second test. The glass pane taken from the DC-3 windshield had been left in the metal frame and rubber U-channel in accordance with standard specifications for the part. After the discharge, the frame was found somewhat distorted and blown open slightly at the point of entry of the discharge.

A fourth test was undertaken by making the DC-3 windshield enclosure part of the electrical circuit and passing a discharge over the outer face of one of the front fixed glass panes of the assembly. This produced a blistered surface to the glass material without any appearance of cracks in its lamination. Another electrical discharge was made to pass across the inner surface of the windshield pane just

referred to in the close proximity of the path of the previous discharge. This produced a sand-blasted appearance without any cracked laminations of glass.

Under the conditions of the experiments, the laminated shatterproof glass was not shattered (as by an explosion), inasmuch as the lamination binder material still retained a considerable adhesive and reinforced quality to the broken laminations which made up the complete glass pane. The effect of repeated discharges of high potential resulted in a condition similar to erosion of the surface at the immediate vicinity of the discharge channel.

Of course, the limitations of potential and charge in the laboratory place restrictions on the extent to which the results of the tests can be applied to natural lightning in the most severe form that might be encountered by an airplane. Fortunately, evidence to date leads to the conclusion that the current density in lightning channels of return strokes from ground to cloud is ordinarily less at high levels than near the ground.

APPENDIX III

DATE, TEMPERATURE, AND ALTITUDE ON OCCASIONS OF DISRUPTIVE DISCHARGES
TO AIRCRAFT (ACCORDING TO NACA QUESTIONNAIRES TO END OF 1944)

Date ¹	Temperature ² (°F)	Altimeter (ft)	Height above ground (ft)
07XX22	---	6,000	3,500
032535	28	14,000	13,400
040435	-5	18,000	16,700
060235	40	11,000	10,200
060135	36	10,000	9,000
092235	---	15,000	14,000
102735	40	6,000	5,000
110235	25	12,500	11,800
101936	---	11,000	-----
032437	---	7,000	6,000
040237	35-40	4,000	3,300
093037	35	11,000	5,000
011738	---	7,000-7,500	-----
030838	34	8,000	2,000
031138A	29	3,500	-----
031138B	28	3,000	2,000
032238	38	9,000	8,000
032638	10	13,000	9,550
³ 032938A	30	10,500	8,000
041338	35 approx.	7,000	6,400
050238	34	11,000	-----
051638	33	7,000	6,000
051738	---	6,000	-----
061138	---	15,000	-----
061838	---	11,000	11,000
³ 072338	---	10,000	10,000
092138A	28	9,000	9,000
092138B	28-31	8,000	-----
092638	40 approx.	10,000	9,000
100238	25	12,000	7,000
102638	28	8,000	7,000
110138	10	15,000	13,000
120238	31-34	7,000	6,300
010539	---	4,000	3,800
032139	32	11,000	4,200

See footnotes at end of table.

Date ¹	Temperature ² (°F)	Altimeter (ft)	Height above ground (ft)
041339	30 approx.	8,000	7,100
043039A	10	10,000	8,500
043039B	30	6,500	4,600
072739	82	900	900
081239	50	6,000	2,500
082639	60	10,500	-----
101939	35	11,500	12,000
102139	60	4,000	2,000
102739	36 approx.	6,000	3,000
110739	24	7,000	6,200
032040	38	4,000	4,000
031840	34	6,000	5,000
032340A	35	8,000	5,500
032540	28	9,300	7,300
040340	---	11,000	-----
042640	30	7,000	6,500
043040	30	11,000	10,000
050140	34	9,000	9,000
051940	32	11,000	6,000
052540	32	8,000	7,400
052640	60	6,000	4,500
052840	24	12,000	11,400
053140	35-40 approx.	11,000	9,200
060440	32	11,000	5,000
061840	36	11,000	10,000
062040	28	6,000	4,500
062540A	30	8,000	7,200
062540B	33	8,000	6,700
062640	28	9,000	7,200
083140	32-41	10,000 approx.	-----
091540	34	11,000	10,500
092240	21	18,000	-----
092940A	50	9,000	9,000
³ 092940B	26	8,300	-----
102540	---	6,000	5,800-6,000
110240	37	6,000	4,500
110440	32	7,000	3,800
110540A	48	8,000	6,600
110540B	37	9,000	7,700
111840	34	8,000	4,000
011141	31	10,000	4,000

See footnotes at end of table.

Date ¹	Temperature ² (°F)	Altimeter (ft)	Height above ground (ft)
011641	56	10,000	3,000
030241	15	12,000	7,000
031641	22	6,000	5,000
032341	19	12,000	5,500
032641	28	7,500	2,000
032841	35	7,600	7,500
033041	26	9,000	9,000
040141	32	10,600	3,000
040941A	28	9,000	8,800
040941B	24	11,000	6,000
041041	33	8,000	7,100
041141	25	14,000	14,000
041441	28	7,700	6,200
041541A	18	12,000	5,000
041541B	33	3,000	2,750
041641	33	3,500	3,000
050141	31	8,000	7,000
051741	32	7,700	6,600
052641	23	11,000	6,700
060441	27	13,000	4,000
061541A	32	11,000	10,000
061541B	34	11,000	9,000
061541C	68	1,200	200
061641	34	7,000	6,400
061741	20	15,000	14,000
070341	33	10,000	9,000
070641	54	11,000	6,000
080441	59	8,000	8,000
081041	32	13,000	11,000
081141	---	14,000	13,000
082441	28	14,000	7,000
090141	68	7,000	7,000
091841	36	14,200	14,200
101041	31	5,000	3,700
101541	32	13,000	13,000
112641	39	8,000	8,000
120241	30-32	9,500	----
012742	31	9,000	8,000
020442	33	9,000	8,000
022442	28	7,000	6,850
031142	34	6,000	4,000

See footnotes at end of table.

Date ¹	Temperature ² (°F)	Altimeter (ft)	Height above ground (ft)
042042	28	11,000	7,000
050642	32	9,000	8,000
110942	40	8,000	7,400
120542	30	11,500	7,500
121842	30	10,000	6,300
012343	32	7,000	6,000
020443	31	7,500	6,300
020843	38	3,500	3,500
022643	25	4,000	4,000
032743	30	11,000	8,500
040743	32	11,000	9,500
040843	---	---	---
040943	34	6,000	6,000
041543	85	5,000	3,600
042843A	35	5,000	4,500
042843B	32	5,500	5,000
051543	36	9,000	4,000
060643	76	6,000	6,000
091043	31	9,000	8,200
092543	32	6,000	5,500
101543	35	11,000	7,500
103043	32-35	8,000	4,000
110243	30	6,000	5,650
121843	28	9,000	6,500
010244	28	6,000	6,000
022244	32	14,000	13,000
022544	32	9,500	9,500
030344	32	8,000	5,800
032144	32	9,000	6,000
040444	20	6,000	6,000
041344	29	8,000	6,500
041444	---	4,000	3,300
042244	40	8,000	5,000
050144	32	6,000	6,000
050544	33	4,500	4,200
050744	32	10,000	3,700
052644	32	13,000	5,000
053144	31	9,000	9,000
062044	33	9,000	6,000
062144	30	10,000	6,000
062344	42	13,000	10,500
062444	32	12,000	5,000

See footnotes at end of table.

Date ¹	Temperature ² (°F)	Altimeter (ft)	Height above ground (ft)
062644	33	13,000	8,500
070344	—	—	—
080544	78	690	0 (gn ground)
081744	40	13,500	13,500
090444	—	2,000	500
090744	59	9,500	9,000
092344	34	15,000	7,000
101144	48	8,000	8,000
112644	—	—	—

¹Code for dates: First two figures represent month (01 - Jan., 02 - Feb., etc., 12 - Dec.). Second two figures represent day of month (01 - first day, 10 - tenth day, etc., XX - unknown). Last two figures represent year in 20th century (22 - 1922, 35 - 1935, etc.). When there are two or more cases on the same day, the one of earliest time is designated by the letter A, the next in order of time by B, etc.

²Temperatures were not corrected for airspeed.

³Southern Hemisphere.

APPENDIX IV

FREQUENCY DISTRIBUTION OF TEMPERATURE ON THE OCCASIONS OF
 DISRUPTIVE DISCHARGES TO AIRCRAFT FOR THE PERIOD
 MARCH 1935 THROUGH DECEMBER 1944

Temperature (°F)	Number of cases	Temperature (°F)	Number of cases	Temperature (°F)	Number of cases
-5	1	34	11	28-31	¹ 1
10	3	35	6	30-32	1
15	1	36	4	31-34	1
18	1	37	2	32-35	1
19	1	38	3	32-41	1
20	2	39	1	35-40	1
21	1	40	5	30 approx.	1
22	1	42	1	35 approx.	1
23	1	48	2	36 approx.	1
24	3	50	2	40 approx.	1
25	4	54	1	35-40 approx.	1
26	2	56	1	Unknown	18
27	1	59	2		
28	15	60	3		
29	2	68	2		
30	10	76	² 1		
31	7	78	² 1		
32	23	82	1		
33	10	85	1		

¹When a range is indicated, the report on the case in question gave for the temperature not a single figure but the specified range within which the temperature must have occurred.

²Occurred while aircraft was on the ground.

Note: Temperatures were not corrected for airspeed.

APPENDIX V

ESSENTIAL METEOROLOGICAL PROCESSES

Certain meteorological processes or combinations of processes almost invariably are required for the development of the clouds, thunderstorms, and precipitation in connection with which electrical discharges to aircraft have been experienced. Generally speaking, these processes act in the following way: Relatively warm, moist air ascends by convection or is caused to be lifted in some fashion until at some level condensation of water vapor begins and clouds start to form; the saturated air then either undergoes convection or otherwise is lifted (as a cloud) to or above the level at which freezing of liquid water occurs and ice crystals, snow, and so forth, form. Ultimately, therefore, the end result is a cloud consisting of liquid-water droplets in its lower portion and ice crystals, snow, or some other form of frozen precipitation in its upper portion.

A comprehension of the processes of atmospheric convection and lifting are essential to a full understanding of this study. (See appendix I.)

First, in regard to convection: Convection depends on the buoyancy of parcels of air which ascend because they are warmer, hence less dense (i.e., "lighter"), than the surrounding air, which sinks because of its greater density. Convection is therefore an overturning process in atmospheric layers. Convection occurs when air layers are unstable, that is, have a greater than dry-adiabatic lapse rate under unsaturated conditions, and a greater than wet-adiabatic (or pseudoadiabatic) lapse rate under saturated conditions. (Lapse rate is the rate of decrease of temperature with height: The dry-adiabatic lapse rate is 0.55° F per 100 ft, and the wet-adiabatic lapse rate averages roughly 0.33° F per 100 ft.) Air layers may be caused to become unstable for unsaturated conditions by any of the processes indicated in the outline below under items I, II, and III. Air layers may be caused to become unstable for saturated conditions by any or all of the processes indicated in the outline below. Convection of parcels of air unsaturated with water vapor causes cooling of the air by adiabatic expansion. When the convection proceeds to such a height that the air is cooled to the dew point of the vapor, condensation occurs and clouds are produced. Convection of saturated air is essential for the formation of cumuliiform clouds. These clouds are not of the cumulo-nimbus

subclass until ice crystals or snow are formed at their tops. Falling of the crystals or snow through the liquid water cloud below produces rain in showers.

Second, in regard to lifting: Lifting depends on the forcible ascent of layers of air more or less as a body through the wedge action of fronts, mountain slopes, and so forth, or through the "squeezing" action of horizontal convergence. The various more important modes of lifting found by meteorological science are outlined below under items IV, VI, and VII. Sufficient lifting of unsaturated air may lead to condensation of water vapor and cloud formation by adiabatic cooling as explained under Convection. Unhindered lifting and horizontal convergence cause vertical stretching of air layers. When the layers are unsaturated and absolutely stable (i.e., have a lapse rate less than the wet-adiabatic, thus being stable for saturated air), the vertical stretching cools the top faster than the bottom by adiabatic expansion, thereby increasing the lapse rate. In this manner it is possible to achieve conditional instability (i.e., a state where the actual lapse rate exceeds the wet-adiabatic value, but is less than the dry-adiabatic value). A conditionally unstable layer is unstable when the air becomes saturated. Overturning by convection of saturated air within the layer, and the development of cumuliform clouds can result under these circumstances. The sufficiently sustained action of lifting and horizontal convergence on air layers that are convectively unstable and also initially absolutely stable can bring the layers to a state of conditional instability with saturation prevailing in their lower portion. This final situation is actually unstable and leads to overturning, convection currents, and cumuliform clouds. On the other hand, when clouds form in absolutely stable air, they tend to lie in layers (stratiform) and are not so likely to yield an electrical discharge to an aircraft. (An exception might occur when condensation is in the form of snow, and turbulence exists by passage over rough terrain.)

In every case convection and lifting depend on the action of certain processes upon air masses of suitable characteristics, described in section 10. (By "air mass" is meant an extensive body of air within which the conditions of temperature and moisture in a horizontal plane are essentially uniform.)

The processes which produce instability and hence lead to the convective activity necessary for cumuliform cloud and thunderstorm development are outlined under Heating of

an Air Mass from Below, each process being capable of giving rise, more or less, to its own type of thunderstorm.

In practically every variety of thunderstorm an important phenomenon connected with propagation of the storm is cooling of the air by cold rain or other precipitation that falls from high levels into the region below the leading portion of the cumulo-nimbus cloud base. The cooling effect results largely from evaporation of the cold rain in the unsaturated air beneath the forward part of the cloud. The cooling causes the air to increase markedly in density, which produces rapid sinking. When the resultant cold air reaches the ground it runs ahead of the cloud, advancing against the warmer, moist air in the direction of the storm motion like a miniature cold front. (See IV, 1, below.) This front exerts a lifting action analogous to that of a shovel, thereby producing further convection and condensation in the line of advance of the storm, and aiding in its propagation.

I. HEATING OF AN AIR MASS FROM BELOW

1. By contact with sun-warmed ground, where the air mass is characteristically warm and moist, but the ground locally hotter because of its excellent absorptive qualities for solar radiation

(This is responsible for the "local convective" or "heat" type of thunderstorm, which is very common in the summer. Storms of this kind occur more or less in isolated fashion and can readily be circumnavigated. Light winds are more conducive than moderate or strong winds to this type of thunderstorm, since excessive shearing in the vertical hampers "chimney-like" vertical convection, which is essential for the development of these thunderstorms. The same is true of thunderstorms of the type outlined in the next paragraph.)

2. By contact with a surface warmer than the air mass which is characteristically cold relative to the surface, generally being of polar origin

(This is usually responsible for thunderstorms in cold air masses rapidly invading a considerably warmer, often moist region.)

II. COOLING AT TOP OF AN AIR LAYER

1. By outgoing radiation from the top of a deep, moist layer of air overlain by a deep, relatively dry layer, the latter allowing radiation to pass readily to space

(This is a possible cause of nighttime thunderstorms sometimes observed at high levels over the Plains states. The top of a cloud layer is a good radiator and loses considerable heat when dry air is above. The moist air mass must generally be at least 10,000 to 12,000 feet deep for thunderstorms to develop in this manner.)

2. By evaporation of rain or melting and evaporation of snow falling into the top of an unsaturated layer.

(This has a bearing on the propagation of prefrontal thunderstorms, on the growth of various types of thunderstorms, in addition to cumulo-nimbus and fracto-cumulus clouds, and also on the development of tornadoes. The evaporation at the top of the layer causes cooling which steepens the lapse rate to a point where instability results. Convection then occurs. When exceedingly steep lapse rates are thus formed, convection becomes extremely vigorous and tornadoes may be created. Convective instability is a prerequisite in these cases.)

III. ADVECTION OF WARMER AIR IN LOWER PORTION AND/OR COLDER AIR IN UPPER PORTION OF A LAYER.

1. By advection or overrunning of potentially cold air over potentially warmer air

(This occurs to a certain extent at rapidly advancing cold fronts, also called squall lines. Such actual overrunning probably does not extend beyond five miles or so, in the form of an overhanging wedge of potentially cold air which entraps potentially warmer air beneath. Overrunning may also occur for a brief time in leeward valleys containing stagnant warm air, when a cold front under the impetus of a steep pressure gradient arrives at the crest of the ridge and abruptly bursts out over the valley. Violent and dangerous thunderstorms and convection currents result from overrunning. The foregoing depicts some extreme forms of overrunning of potentially colder air over potentially warmer air. Less extreme cases are observed more

commonly as a result of advection of a stratum of air under circumstances such that differential changes occur in the virtual potential temperature of the lower and upper portions of the air, usually with cooling aloft and/or warming below, leading eventually to the development of a condition unstable for unsaturated air. At least two writers on the subject have shown that such advective changes may explain the inception of nocturnal thunderstorms in the midwestern states, (See references 18 and 19.) It is probable that sometimes the advective changes represent the intercalation of potentially cooler and/or warmer strata of air between other strata by flow which may be characterized more or less as isentropic. The advection of humid air in the lower portion and dryer air in the upper portion of the advancing stratum also tends toward the development of an unstable condition. Such modifications may also give rise to convective instability, so that lifting of the air mass by any process (e.g., by action of fronts, topographic slopes or horizontal convergence in the underlying stratum) may release the instability. The occurrence of horizontal convergence in an unsaturated stable advective layer augments the lapse rate and prepares the way for eventual development of instability for unsaturated air within that layer by the differential changes outlined above.

In the neighborhood of mountains or plateaus, marked upper-air temperature changes may result from advection following insolation heating or radiational cooling of the air in contact with the high ground, and the liberation of latent heat of condensation possibly due to orographic lifting. The insolation heating results in steep lapse rates and strong convective activity which may be transported to leeward by the winds.) (See reference 18.)

2. By advection or underrunning of potentially warm air beneath potentially colder air

(This is probably effective in connection with the development of prefrontal and some other type thunderstorms. (See V.) It can operate if in some manner the lower air is caused to become potentially warmer than the upper air immediately to the windward. The latter result can be brought about by release of latent heat of condensation within saturated convection currents initiated at low levels or by other means of heating below as illustrated under I. Underrunning or shearing of the lower air beneath the potentially colder air ahead can take place as a result of the convergence and other effects stemming from the abrupt intrusion of a rapidly moving cold front into a warm air mass.

The shearing process is perhaps most likely to occur in warm air masses or warm sectors of cyclones ahead of such fronts. The underrunning is believed to be most effective for producing eventual instability aloft when: (a) a body of warm air flows from a warm toward a colder region so far as concerns the temperatures at the levels occupied by the given air, provided the lower boundary of the mass is not in contact with the ground; (b) a cyclonic curvature is imparted to the motion of the warm air as the cold front moves closer to the course being pursued by that air; and (c) the horizontal temperature gradient (in the meteorological sense, i. e.; from high to low temperature) immediately above the upper portion of the warm air mass has approximately the same direction as the motion of that mass in the region where it experiences the stated curvature - that is, the warm air moves so that its upper reaches progress from warmer toward colder conditions aloft. The cyclonic curvature results from the convergence and the change in curl of the local pressure field which occur in connection with the portion of the trough immediately ahead of the advancing cold front. Thus, prefrontal currents may be caused to become unstable aloft at possibly 8,000 to 12,000 feet elevation as is often manifested by the development of alto-cumulus-castellatus clouds. These generally result from convection not originating at the surface. The liberation of latent heat of condensation makes the cloud level warmer than the overlying air in the active stage of cloud development so that the lapse rate may be made steeper as the underrunning progresses more or less along the upper temperature gradient.

NOTE: In this discussion it should be understood that the purely thermodynamic criterion of instability of unsaturated air is the decrease of virtual potential temperature with altitude.)

IV. FRONTAL LIFTING OF A RELATIVELY WARM, MOIST AIR MASS

1. By cold-front action

(This depends on the lifting action of a wedge of relatively cold, dense air when in moving along the surface it thrusts under a warmer, lighter air mass and tends to spread out beneath the latter, thus raising it off the surface. Rapidly moving cold fronts are equivalent to squall lines, with which line-squall thunderstorms are associated. Cold-front thunderstorms can be very intense, especially when the

warm air mass is very moist and conditionally unstable. Steep cold fronts which result from rapid motion of the cold air mass over rough ground are likely to yield violent thunderstorms and cumulo-nimbus clouds with powerful convective currents over a relatively narrow zone. When the cold-front surface of discontinuity slopes only gradually upward, the thunderstorms and clouds may be spread out over a wide zone. The moisture content, condensation level, and degree, extent, and character of instability in the warm air mass are controlling factors in regard to the vertical development of the clouds and width of the zone involved. Item I, 2 is also important in connection with this matter, when penetrative convection from beneath the cold-front surface of discontinuity occurs.)

2. By warm-front action.

(This is effective when a relatively warm, moist air mass which is conditionally unstable or is convectively unstable and becomes conditionally unstable by lifting, actively flows up the slope of a warm-front surface - that is, the surface of discontinuity between an underlying wedge of cold, dense air and warmer, lighter air aloft that is pursuing and overtaking the former. Cumulo-nimbus clouds and thunderstorms produced by this mechanism can be spread out over a wide zone.)

3. By occluded- or upper-front action

(When a cold front at the leading edge of an advancing wedge of cold air overtakes a warm front ahead of which is another wedge of cold air sloping in the other direction, the denser (colder) of the two begins to lift the other upward. The warm air previously between the surface fronts is lifted off the ground and is entrapped in a trough between the two wedges. An upper front, either of the cold-front or warm-front type is produced in this way, giving rise to the warm-front or cold-front type of occlusion. An upper front may thus move along the sloping surface of the denser wedge, or along a horizontal upper boundary of a shallow underlying cold, dense mass of polar air. The latter variety of upper front is not infrequently observed over the eastern slopes of the Rockies and adjoining plains region when the less-cold air crosses from the Pacific side and overrides the shallow, dense layer which came from the north or northeast. Upper cold-front action is essentially similar to surface cold-front action. High-level cumuliiform clouds and thunderstorms often derive their energy from the release of conditional instability possessed by the warm air mass being lifted in the occlusion trough aloft. Tornadoes commonly develop along an upper-cold front advancing against a convectively unstable, warm, moist air mass aloft, moving relative to the colder air so that intense cyclonic vorticity is generated between them.)

4. By lifting action along a stationary (or quasi-stationary) front

(Even if the front of a cold, dense air-mass wedge is stationary or apparently stationary, lifting of a warm, moist air mass can take place so long as the latter has such a motion relative to the front that it will ascend the frontal slope of the wedge. When the warm air mass is characterized by instability¹ during the ascent and condensation occurs, cumuliform clouds and possibly thunderstorms may develop. These may cover a wide area and persist for some time as long as a supply of warm, moist air is forced to glide up the slope.)

V. PREFRONTAL OR PRECOLD-FRONT ACTION

(Prefrontal thunderstorms may run ahead of the surface cold front in the warm sector by distances sometimes ranging from several miles up to 60 miles or, perhaps, as much as 200 miles. Prefrontal thunderstorms may occur at all hours of the day or night but appear to be most frequent in the late afternoon or early evening, when sharpening and acceleration of the cold front is pronounced. They apparently are due to a combination of causes, notably horizontal convergence (see VII), underrunning of potentially warm air beneath potentially colder air (see III, 2), evaporation of rain falling into top of an unsaturated layer (see II, 2), and heating of an air mass below by contact with sun-warmed ground. (See I, 1.) Lifting and increased conditional instability due to convergence sets off condensation and produces strongly convective cumulo-nimbus clouds ahead of the cold front in the conditionally unstable, warm, moist air mass against which the cold front is rapidly advancing. As explained in III, 2, underrunning is an important contributing factor since it leads to continuous generation of instability at the top of the saturated convection current as it is carried horizontally by the winds at lower levels and propagates the convection to high levels. After the precipitation from the cumulo-nimbus clouds becomes heavy, the air cooled by evaporation sinks because of increased density and runs ahead along the surface as a precursory cold front. This exerts its own lifting action and can initiate other cumuliform clouds or augment the convective activity of the existing clouds. Such local convection as is present in the warm air mass assists in the growth of the cumulo-nimbus clouds and thunderstorms by contributing energy and allowing additional water vapor to be tapped from the lower strata. If the higher air

¹Conditional instability.

²The cooling is especially pronounced and frontal action more energetic and extensive if the air is convectively unstable.

is very dry, radiational cooling at the top of the saturated cumuliiform clouds can create fresh instability at night and give an added impetus which leads to further vertical growth rather than dissipation of the clouds.

A line of thunderstorms may thus be brought into being far in advance of the surface cold front. The attendant rain showers, originating near the freezing level, are often particularly heavy and descend in "gushes" when the sustaining convective currents and electrical forces fail. As the cold rain falls out of the cloud, evaporative cooling at the top of the lower stratum of unsaturated air increases the lapse rate and with it the instability. Convection is thereby intensified. The great contrasts between the resultant updrafts and downdrafts create regions of violent turbulence which are very hazardous to aircraft. Where the downdrafts strike the surface very gusty winds accompanied by heavy showers are experienced, in the characteristic fashion of line squalls. Sometimes hail and occasionally tornadoes occur in conjunction with prefrontal thunderstorms. The most dangerous conditions may therefore be encountered under the stated circumstances. See IV, 3, regarding tornadoes.)

VI. OROGRAPHIC LIFTING

(This is due to the lifting action of upward-sloping terrain, as mountains, hills, and coastal slopes. Orographic lifting therefore is only largely effective on the windward side of a barrier. When the wind velocity component perpendicular to the mountain ridge is strongest, the most severe conditions are likely to develop, other things being equal. Cumuliiform clouds and thunderstorms readily form when the air mass being lifted is warm, moist, and conditionally unstable. They may also develop when the air mass is convectively unstable and the lifting is sufficient to release the instability. When cold-front action and orographic lifting operate simultaneously, the thunderstorms produced are likely to be of greater intensity than if either agency alone had acted. Cumulo-nimbus clouds which originate orographically are usually characterized by strong turbulence. Windward slopes exposed to strong sunshine and thereby warmed are conducive to the growth of such clouds by virtue of a chimney-convection effect. Heavy icing conditions are often experienced in the sub-freezing temperature region of cumulo-nimbus and other clouds, especially where turbulence is strong as in the circumstances described above. Powerful downdrafts on the

leeward side of mountains often introduce additional hazards to be avoided.)

VII. HORIZONTAL CONVERGENCE

(This is due to a distribution of winds within a given region such that there is a net inflow of air into it. When the inflow is near the surface, this causes vertical lifting of the superposed air layer. The latter layer suffers a vertical stretch by this upward motion if higher layers do not prevent that by excessive resistance, and partake of the motion. Air layers increase their lapse rate by vertical stretching when the lapse rate is initially less than the dry adiabatic. Consequently, absolutely stable air layers may become conditionally unstable by this process, or already conditionally unstable layers may be made more unstable thereby. A similar effect is produced within layers themselves subjected to horizontal convergence. The adiabatic cooling which vertical stretching induces at the top of a layer undergoing convergence or being lifted also results in condensation of water vapor and cloud formation. A convectively unstable layer which is vertically stretched or lifted by horizontal convergence may be impelled to release its potential convective energy through overturning, provided the stretching or lifting is sufficient. Horizontal convergence therefore is a potent factor for modifying the condition of atmospheric layers so that they may become more favorably disposed to internal convection and the development of cumuliform clouds and thunderstorms. Horizontal convergence, whether or not acting in cooperation with any of the other atmospheric processes previously mentioned, is capable of producing cumuliform clouds and thunderstorms in air masses. When the cooperation takes place, the likelihood of thunderstorm formation is greatly increased.)

ADDITIONAL FUNDAMENTAL CONSIDERATIONS

A discussion of the essential meteorological processes involved in the development of thunderstorms would not be complete without at least a qualitative consideration of some deductions from theory¹ regarding the thermodynamics and dynamics of cumulo-nimbus clouds. The qualitative consideration follows.

¹Based largely on the studies outlined in the author's paper (reference 20), to which are added some conclusions from his succeeding investigations.

VIII. EVAPORATIVE AND RADIATIVE PROCESSES

(First, consider certain phenomena involved in the vertical development of cumulus and cumulo-nimbus clouds, especially at and near their upper and side exterior surfaces.

The immediate environment of an actively growing cumuli-form cloud must be conditionally unstable. During the growing stage of a column of saturated air undergoing penetrative convection, such as is found in a cumulus-congestus cloud, latent heat of condensation is liberated within the ascending air as water vapor condenses to form water droplets. Just within the summit of such an actively rising column, which usually assumes a cauliflower-like shape, the heat thus released causes the saturated air to be warmer than the overlying air. Moreover, the air within the upper portion of the cloud dome contains relatively warm cloud droplets and has a greater absolute vapor content per unit volume than the unsaturated environment. Accordingly, vapor diffuses and is transported by turbulent eddies from the head and sides of the ascending column into the surrounding, less-moist air. Since this reduces the relative humidity in the spaces immediately surrounding the cloud particles, the water droplets evaporate to some extent near the outer surface of the convective column. This process requires latent heat of evaporation (nearly 600 calories per gram at $0^{\circ} 0$), which is absorbed from the droplets and the air in intimate contact with them. The evaporation can proceed until the immediate environment of the column becomes saturated with water vapor, a state which serves to limit the phenomenon.

From the above considerations, it follows that in the absence of direct solar heating the outermost "skin" of saturated air at the crest and often, too, around the side walls of the ascending current becomes cooled. Important factors controlling the mechanism are the differences between the equivalent potential temperatures and absolute humidities at the cloud surface and its immediate environment. The steeper the outward directed gradients of these elements the more rapidly does the cooling occur and the greater its degree. The process thus steepens the temperature gradient between the above-mentioned skin of the cloud and the saturated air immediately within. At the crest of the cloud this signifies a local steepening of the lapse rate which may eventually lead to the development of instability for saturated air. In consequence of this, small convection currents force their way upward through the top surface of the cloud and penetrate

possibly a short distance into the overlying unsaturated air. These droplet-laden currents, which are probably wisp-like, moisten the superposed air. It therefore cools to some extent as a result of evaporation of the water particles.

The cool air forming the (shaded) outer sheath of cloud and the air immediately above the cloud crest which is cooled by the evaporative process just outlined tend to sink relative to any warmer, less-dense parcels of air forced to the same levels by convection. In this manner a descending current may be produced in the outer sheath of cloud when the surface is not exposed to the direct rays of the sun. So long as the air in the descending current is colder than its environment, it buoys up and displaces warmer air present both at its level and aloft. Involved in this process is the well-known "chimney effect." By virtue of this, the greater the vertical extent of the cloud mass and the greater the difference in mean density between the column of warm air in the generally ascending core of the cloud and the column of cooler air in the generally descending region of the cloud wall, then the greater the resulting vertical velocities and transports both up and down.

Among the factors controlling these effects is the reciprocal action of displacement which connects the behavior of parallel, adjacent, oppositely moving vertical currents. Thus, an ascending current produced by physical causes in one column may promote, by displacement, a descending current in an adjoining column, and vice versa. The extent and velocity of any current created in this manner depends on the net volume of air simultaneously flowing per unit time in the opposite direction nearby through the various levels, taking account of modifications due to frictional effects, turbulence, and lateral exchange of momentum around the boundaries of the currents.

Consequently, a swiftly moving extensive updraft in the core of a thunderstorm circulation cell may have as a concomitant an approximately similar integrated volumetric transport in the opposite direction manifested by descending currents in the sheath of the cloud and subsidence in the environment thereof. The inverse is likewise possible; so the two actions are mutual and inseparable. Hence, marked subsidence in some zone within or near the cloud may intensify the upward convection within the core, while strong updrafts in one area may influence strong downdrafts elsewhere in the neighborhood.

With the more towering cumulus and cumulo-nimbus clouds, therefore, the more marked can become the contrast in vertical

velocities between the two adjacent streams of air moving in opposite directions. Thus may arise a steep horizontal gradient of vertical velocity in the transition zone between the sheath and central core of the cloud circulation system. In this zone, rapid fluctuations, of considerable magnitude in both vertical and horizontal accelerations, and severe turbulence, are to be expected. Accordingly, the air in and near this zone, being generally laden with ice and water particles, often participates in processes leading to an intensive generation and separation of electrical charges, with resultant formation of steep potential gradients and attendant likelihood of development of disruptive discharges.

An important consequence of the processes described is that an important share of the driving mechanism of the vertical circulation system of the growing cumuliform cloud stems from the buoyance imparted to the warmer air in the core by the cooler air which sinks in the sheath of the cloud. It may be remarked that this permits the continuation of a circulation after the supply of warm, convective bodies of air from the underlying atmosphere has been cut off. Added in great measure to the foregoing source of motive power is the latent energy liberated by condensation, freezing, and sublimation within the cloud, as well as the energy derived from any buoyant parcels of air entering its base from below. Not to be forgotten, of course, is the reservoir of potential energy resident in the environment, which yields up some of its store by subsidence.

In studying the factors which control the evaporative-cooling process discussed above, it is necessary to consider ventilation. This is determined by the steepness of the gradient of air velocity measured between the surface of the cloud and the adjacent unsaturated air - that is, a marked relative velocity in a short distance between the cloud particles in the surface and the contiguous clear air represents a situation favoring evaporation.

Thus, other conditions remaining equal, and excluding areas where condensation predominates, the portion of the surface of the cloud which receives the most ventilation tends to yield the most evaporation, greatest cooling, and most rapidly descending currents. Consider, for example, the variations in rate of evaporation at the crest and along the walls of a towering cumuliform cloud associated with an environment wherein the wind velocity varies with altitude. Thus, when the wind velocity increases with height, it is to be expected that the upper, windward portion of the cloud is

affected by a greater rate of ventilation than the upper, leeward portion. The reverse is to be expected when the wind velocity decreases with height. These factors are conducive to the development of a differential in the vertical velocities manifested on the windward and leeward sides of the cloud, thus influencing its cellular structure. Moreover, a steep vertical gradient of wind velocity near the crest of the cloud, especially when associated with a steep lapse rate, materially influences the rate of evaporative cooling at the crest and the degree of turbulence and eddy motion generated in its vicinity.

Another phenomenon of importance in connection with the development of clouds hinges on the fact that water droplets have an emissivity which is much greater than that of relatively dry air. Hence, the top and the upper, exterior sides of a cauliflower-shaped cloud may lose considerable heat by radiation when the air which the cloud exterior "sees" is dry and colder, provided incident solar radiation is weak or absent. This process also intensifies the cooling at the outer portion of the cloud and enhances the cooling by evaporation previously discussed. It is especially effective at night.

The cooling at the shaded top of the cloud jointly by radiation and evaporation may lead to creation of instability in the upper sheath of cloud. Convection currents result within this layer as explained in the third paragraph of this section (VIII). However, by virtue of the cooling, a thin inversion which hampers convection tends to form immediately above the cloud. But, sinking of the cool air of this inversion by gravity and the sweeping action of advective currents across the cloud top may, because of turbulence and translational motion, render the inversion negligible. At favored points, then, penetrative convection from the underlying unstable cloud sheath may force its way through the slight inversion layer, and permit continued upward propagation of the cloud, if convective and conditional instability prevail aloft. In addition, if the cooling is both extensive and considerable on cloud top and wall, the cooled sinking air displaces warmer air and intensifies upward convection elsewhere in the cloud.

When there is strong, direct incident, solar radiation on the exterior surface of the cloud, the cloud particles and associated saturated air are warmed up. Since the contiguous, unsaturated air around the cloud is not heated to the same extent, a steeper temperature gradient than existed before is established. At the top of the cloud, this gradient, on becoming sufficiently strong, permits the vertical, upward propagation of convection currents and hence the upward development of the cumuli-form cloud structure. If the unsaturated air overlying the

cloud is especially dry, the convection currents from the upper portion of the cloud penetrating that air may mix with the environment and lose moisture by rapid evaporation of the entrained cloud particles. Eventually, the moistening process in the overlying unsaturated air may permit the further vertical progress of the cloud development, provided the original lapse rate of the air was steep enough to be favorable to the attainment of a conditionally unstable lapse rate. These phenomena strongly influence the diurnal variation of cloud evolution, especially in connection with those of the cumuliiform variety.

IX. THERMODYNAMICAL LAPSE RATE STEEPENING AT TOP OF GROWING CONVECTIVE CLOUD

During the active growing stage of a cumulus congestus the convection currents within the core of the cloud thrust the upper saturated surface of the cloud vertically against the overlying, unsaturated air. Inasmuch as the saturated air cools at the wet adiabatic rate and the unsaturated air cools at the dry adiabatic rate, the latter cools to a greater extent than the former. This steepens the lapse rate between the two contrasting bodies of air and aids in the upward propagation of the currents by convection as they repeatedly are forced toward the crest of the cloud, with probable intervening periods of lapse in vertical velocity. The process is most effective when convective instability prevails; that is, when the equivalent potential temperature decreases with altitude.

X. EFFECTS OF DIFFERENTIAL LIBERATION OF LATENT HEATS OF FUSION AND SUBLIMATION IN THE VERTICAL, ATTENDING FALL OF ICE PARTICLES THROUGH A CLOUD OF SUPERCOOLED WATER DROPLETS

Two concurrent related mechanisms exert a profound influence on thermodynamical conditions when a cumulus cloud transforms into a cumulo-nimbus cloud - that is, after ice crystals appear in the upper portion of the cloud.

Liberation of Latent Heat of Fusion

(a) The falling of ice crystals or pellets into an aggregation of water droplets having a temperature below 0°C induces freezing of those droplets which suffer impaction by the

ice particles. As the particles grow in size by ice accretion, they progressively fall faster, sweep out a larger and larger area and strike more supercooled water droplets per unit of time and of distance of fall.

Sedimentation and precipitation cause the larger supercooled water droplets to collect in heavier concentrations at the lower than at the upper levels. (By lower levels, is meant here, a zone immediately above the 0°C level within the body of the cloud, not necessarily near the base of the cloud.) Hence, for each unit volume swept out by an ice particle during descent, greater and greater quantities of water are encountered as it approaches the level of 0°C temperature. Owing to all the factors mentioned above, there is a very marked stepwise increase in the rate of total ice accretion per unit distance of fall of each particle, as the descent progresses. The freezing associated with a process of this character, when applied to a large number of particles, yields a much greater liberation of latent heat of fusion (about 80 calories per gram of water frozen) in the lower portion of the supercooled water stratum of the cloud than at the top of that stratum where the ice crystals are introduced.

In consequence of this differential heating, the temperature lapse rate is steepened and instability may be produced if not already present. With development of such a result, masses of air warmed by this thermodynamic process rise convectively from the lower portion of the given stratum. The larger ice pellets or hailstones fall out of these masses, but the smaller ones, accompanied by most of the remaining supercooled water droplets, are transported upward. In view of this displacement, a fresh supply of ice crystals is enabled to fall into the convective masses at higher elevations and instability is propagated upward until the available water droplets are largely depleted by freezing and evaporation.

Attending the ascent of these masses of air there must be a compensatory descent of cooler air, either surrounding the updraft or occurring in the immediate vicinity of and including the outer portion of the cloud, as previously explained.

Liberation of Latent Heat of Sublimation

(b) The falling of ice particles into an assemblage of supercooled water droplets causes the ice particles to grow by sublimation - that is, by direct transformation of water vapor to frost crystals without passing through the intermediate liquid phase. The rate of diffusion of vapor to the

surface of an ice particle is proportional to the diameter of the particle (here assumed to be spherical for simplicity in discussion) and to the local gradient of vapor density. The rate of diffusion is also considerably influenced by the Reynolds number pertinent to the particle, tending to increase with Reynolds number (but not in direct proportion). This number is equal to the product of the diameter of the particle, the velocity of the particle relative to the gaseous medium, and the air density, divided by the absolute viscosity of the air.

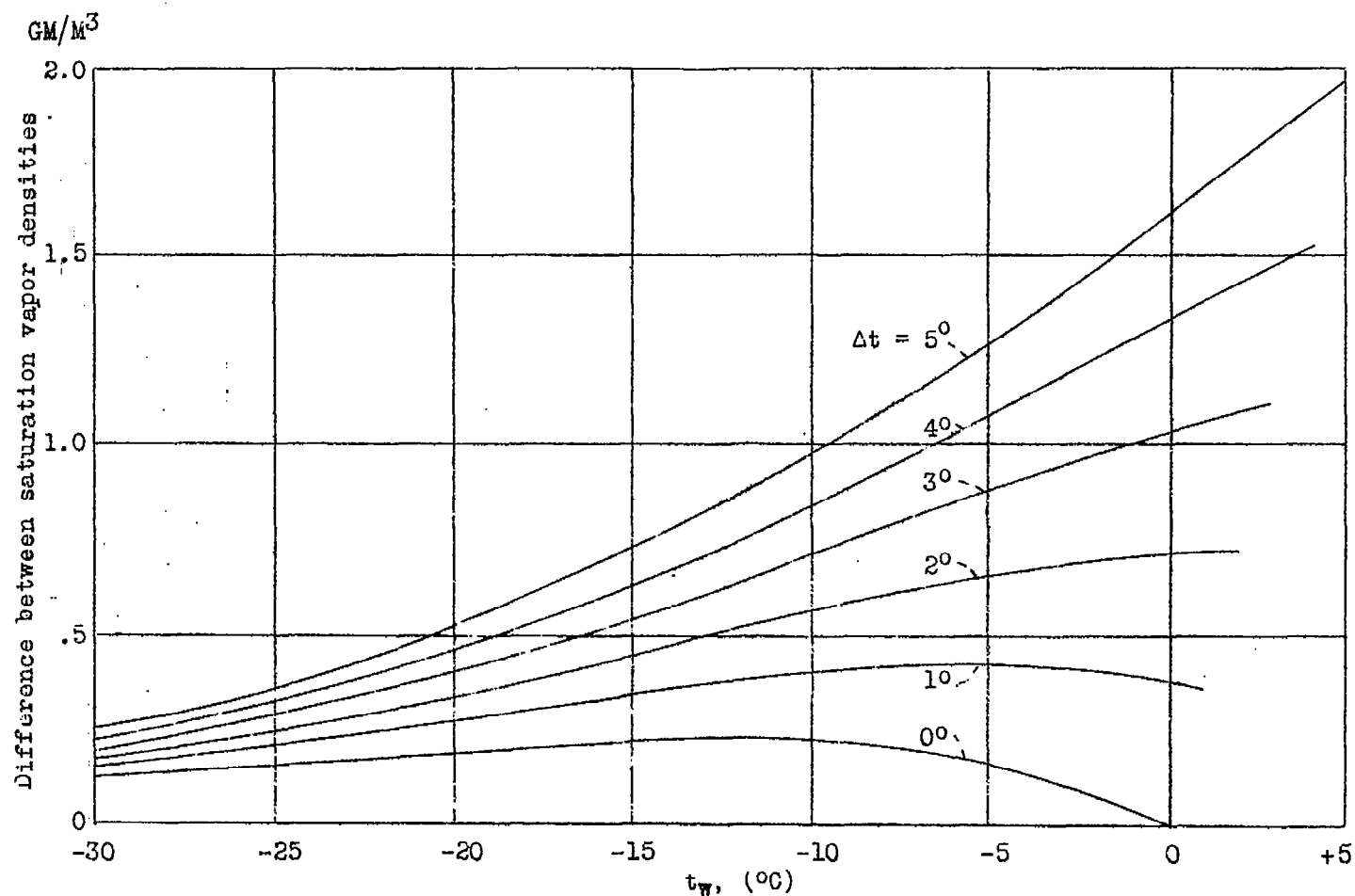
Effect of Variations in Reynolds Number

It is shown in the following discussion that the variations in all three factors (diameter, local gradient of vapor density, and Reynolds number) are conducive to a progressively increasing rate of growth of the ice particle by sublimation during its descent through the cloud of supercooled water droplets, assuming that the space between the droplets was originally saturated with respect to water.

Firstly, as the particle falls it grows manifold in diameter, generally from a few thousandths of a millimeter at inception to perhaps two or more millimeters on precipitating out near the 0°C level. This growth is due to sublimation and to ice accretion resulting from collisions of the ice particle with supercooled water droplets.

Secondly, as a consequence of the difference between the saturation vapor pressures over water and ice at temperatures below 0°C , the local gradient of vapor density directed toward the surface of the ice particle steadily increases during its descent at all temperatures less than -12°C (about 10°F), regardless of whether the particle and saturated vapor are at the same temperature or the particle is colder than the vapor.

At temperatures of the saturated water vapor from -12° to 0°C , the local gradient of vapor density directed toward the particle would also steadily increase, provided the ice particle were 1.3°C , or more, colder than the vapor. This fact is disclosed by the following diagram entitled "Difference between Saturation Vapor Density of a Space over Water at Temperature t_w , and Saturation Vapor Density over a Flat Ice Surface at Temperature t_i , where $\Delta t = (t_w - t_i)$, in $^{\circ}\text{C}$."



Difference between saturation vapor density of a space over water at temperature t_w , and saturation vapor density over a flat ice surface at temperature t_I , where $\Delta t = (t_w - t_I)$, in $^{\circ}\text{C}$.

When the particle falls through a stratum having a normal decrease of temperature with height, it tends to be cooler than the environment. The amount of the temperature difference increases more or less in proportion to the lapse rate and the particle's downward velocity, the latter increasing rapidly with growth of the particle. Differences of 1.3°C or more may be attained when fairly large particles have been formed owing to ice accretion combined with sublimation, and relatively high velocities of fall result.

Where the temperature difference between the saturated water vapor and particle increases beyond 1.3°C , the vapor density gradient toward the particle undergoes a rapid increase as the temperature of the particle closely approaches 0°C .

Thirdly, while the ice particle continues to grow during descent for the various reasons outlined above, its velocity relative to the air undergoes a great increase (from perhaps several thousandths of a meter per second at inception to one or more meters per second on precipitating out near the 0°C level). Since the diameter has undergone a similar relative enlargement, the product of velocity and diameter manifests an even greater augmentation. The air density normally increases by a larger proportion than the air viscosity on descending through an unstable cloud. It follows from these considerations that the Reynolds number pertinent to the ice particle is multiplied many times in the course of the particle's fall through the cloud.

In consequence of the foregoing, the descent of an ice particle must be attended by a progressive augmentation of the flow of vapor to its surface by diffusion. The vapor transforms to frost at the surface, accompanied by a release of latent heat of sublimation proportional to the amount of vapor thus removed from the space.

When a multitude of ice particles falls through a cloud of supercooled water droplets, the trend toward increasing vapor diffusion to the particles with downward progress has, as a concomitant, a greater liberation of latent heat of sublimation in the lower portion of the cloud than in the upper.

Removal of Heat by Evaporation

There is some compensation for this heating by cooling due to evaporation of the water droplets into the space from which vapor has been removed by sublimation. However, the

cooling lags behind the heating since the vapor already existent in a limited space around the ice particles supplies the energy immediately; whereas the cooling does not take place until the slow diffusion of vapor into this space occurs from the vicinity of the water droplets. Hence, by the time the heating due to sublimation begins at lower levels in the cloud, the evaporative cooling has already set in at upper levels. The net heating aloft, due to the addition of latent heat of sublimation and the subtraction of latent heat of evaporation, is very slight compared with the net heating below.

The differential rate of heating between top and bottom of the layer involved is large toward the beginning of the process because of the lag of the evaporative cooling.

The latent heats of sublimation and evaporation of water vapor are 676 and 596 calories per gram, respectively, at 0°C . These data imply that for each gram of frost formed by sublimation on the falling ice particles a considerable quantity of heat will be made available. Moreover, at a given level the amount of thermal energy yielded by sublimation in a given time interval must exceed the amount simultaneously removed by evaporation, at least, in the developing stages of the processes described. This relationship and that outlined under X (a) above (i.e., with regard to freezing) assure that there will be a differential heating which increases downward by virtue of the joint liberation of latent heats of fusion and sublimation in the manner explained.

Hence, there must follow a pronounced steepening of lapse rate and perhaps the establishment of an unstable condition, if not already existent. When instability is created or is intensified, the consequences are as outlined in connection with X (a) above.

Cycles in the Instability-Producing Mechanisms

Energy having been made available for convective activity, large parcels of air are subjected to spasmodic upthrusts, owing to the density differences produced by the differential heat liberation in the vertical column. These upthrusts may readily cause the explosive expansion and vertical development of the cauliflowerlike structures typical of many cumulonimbus clouds in the early stages of their growth. The upward velocity of the bodies of air which thus undergo convection cannot be continued indefinitely, since they sweep up with them

the smaller ice crystals and pellets which are essential for the maintenance of the differential heating described above.

Following the partial collapse of the cauliflowerlike structures to the extent that the ascending masses overshoot the equilibrium level, there is a tendency for a temporary quiescent state to develop. During this interim, the residual small-scale turbulence causes many of the ice particles to collide with numerous supercooled water droplets, thereby producing ice accretion on the particles at an abnormal rate. Directly after this, the falling of the enlarged ice particles into the lower portion of the cloud leads to intensification of the processes previously outlined, so long as upward transport of water vapor into the base of the cloud by convection replenishes the water content lost by sublimation and ice accretion on the particles.

Repeated operations of the mechanism described above are likely to occur because the strong upward convective current entrains the particles at first, thereby preventing them from being deposited into lower levels, and preparing the way for an even more energetic downward convective stage than previously because of the growth of the particles. But this, in turn, leads to the development of another cycle, and the latter to still another, and so forth. The ice particles increase in size periodically with each recurrent cycle, and eventually they may attain the dimensions of hailstones.

The process of development of the particle is analogous in a sense to the process of growth of a snow ball or snow roller tumbling along a fresh snow cover; the larger it becomes, the faster it grows, so that ultimately, a series of such rotations or cycles may culminate in an avalanche.

Analogously, in the case of a thundercloud, the processes described yield a torrent of frozen precipitation.

Instability-Producing Mechanism Located Immediately

below 0°C Isotherm

Consider now the processes that occur when a great mass of relatively cold frozen precipitation particles, some of which may be hailstones, fall into the portion of the cloud occupied by water droplets and air saturated with respect thereto at a temperature exceeding 0°C .

Heat is made available to the air by the following processes involving the frozen particles:

(1) Latent heat of fusion is liberated, owing to the freezing of water droplets which are encountered by the falling particles (the temperature of the latter must be less than 0°C , they having grown at altitudes above the freezing isotherm);

(2) Latent heat of sublimation is liberated, owing to the diffusion of vapor from the saturated space at a temperature above 0°C , to the frozen surface of the particles at a temperature below 0°C , frost accretion thus occurring on the particles;

(3) After the surfaces of the particles have been warmed to a temperature of practically 0°C , by continued exposure to a warmer environment, or when the surfaces become wet at such a temperature, latent heat of condensation is liberated, owing to the diffusion of vapor from the saturated space at a temperature above 0°C to the possibly wet surface of the particles at a temperature of about 0°C , condensation thus occurring on the particles.

It should be noted that the rate of liberation of heat by process (1) depends principally on the concentration of liquid water particles along the path swept out by the frozen particles, the sizes of the two types of particles, the shape and roughness of the frozen variety, the relative velocity between them, the degree of fine-grained turbulence in the environment of the colliding particles, and the density and viscosity of the air. It should be further noted that the rate of liberation of heat by processes (2) and (3) depends on the factors mentioned as controlling process (1), and, in addition, the gradient of vapor density existing at the surfaces of the respective particles, and the coefficient of diffusion of water vapor in air, which in turn depends on the prevailing pressure and temperature. Important in regard to the gradient of vapor density is the difference of temperatures between the surface of the frozen particle and the saturated air, taking into consideration the absolute values of the temperatures.

From a study of the mathematical relationships connecting the factors mentioned, it is found that the trend of the variables in the great majority of cases is such as to be conducive to a greater net rate of evolution of heat by the indicated processes in the zone situated immediately below the 0°C isotherm than in the zone immediately above it, provided both

zones are occupied by the cloud with water droplets having a distribution to be expected normally for cumulo-nimbus clouds.

Heat is removed from the air largely by the following processes involving in some degree the frozen particles:

(4) Heat is conducted from the air to the descending frozen particles, owing to the temperature of the particles being lower than that of their environment;

(5) Heat is radiated from the air, vapor, and water droplets to the falling ice particles, owing to the temperature difference indicated in (4);

(6) Latent heat of vaporization is absorbed by the water droplets as they evaporate in replenishing the vapor removed by diffusion to the frozen particles; and

(7) Latent heat of fusion is absorbed by the frozen particles in melting (generally at 0°C). (A portion of the heat used for this purpose is derived from the heat conducted to the ice particles by impinging droplets of water which have a temperature in excess of that of the frozen particles.)

Certain considerations lead to the conclusion that the rate of removal of heat by processes (4) to (7) is generally less than the rate of liberation of heat by processes (1) to (3) in a thin zone immediately below the 0°C isotherm, at least in the early stages of the precipitation of the frozen particles into the zone. There are also reasons for believing that in active, growing cumulo-nimbus clouds the net rate of heat evolution represented by the sum of the rates (1) to (3) minus the sum of the rates (4) to (7) in the specified zone below the 0°C isotherm is generally greater than the net rate of heat evolution represented by the sum of the rates (1) to (2) minus the sum of the rates (4) to (6) in the correspondingly thin zone immediately above the 0°C isotherm.

To these considerations must be added those resulting from the fact that vapor-laden air is continually entering the cloud base in the active stage, so that latent heat of condensation is yielded as upward convection proceeds in the cloud. The vapor from this source acts to replace that lost by diffusion to the colder, falling particles, and thereby compensates in some degree for the heat loss indicated under process (6).

On accepting the foregoing conclusions, it follows that the layer including the thin zones both above and below the

0° C isotherm is a region where steep lapse rates and instability producing processes will prevail. The reports of soaring pilots appear to bear out these conclusions, in view of the marked turbulence observed on approaching the 0° C isotherm from below in certain types of clouds.

Stability-Producing Mechanism Located Well Below

Level of 0° C Isotherm

After the frozen precipitation particles fall far enough below the 0° C isotherm, the heat removing processes (4) to (7) exceed the heat liberating processes (1) to (3). Then cooling of the layer into which the particles have fallen will ensue. This weakens the lapse rate in a stratum between the thin zone immediately below the 0° C level where heating predominates and the layer just referred to where cooling predominates.

Instability-Producing Mechanism Located Below

Last-Mentioned Stratum

Consider now the stratum below the cooling layer. In the active stage of development of the cumulo-nimbus cloud, the water vapor transported into the cloud at lower levels is caused to condense by vertical convection and latent heat of condensation is made available. Thus is found the possible formation of a transition zone with marked cooling above and heating below. This is conducive to the creation of steeper lapse rates than existed before and possibly marked instability which leads to intense local turbulence in the form of both downdrafts and updrafts.

Development of Turbulence in Relation to Mixing of

Two Forms of Hydrometeors

Turbulent motions will be especially pronounced between columns of descending cold, frozen precipitation or rain formed by melting thereof and columns of ascending, warm saturated air bearing cloud droplets condensed while the air is undergoing convection.

Intermingling of the solid hydrometeors and the cloud droplets due to turbulence in the stratum with temperatures

well exceeding 0°C quickly tends to produce melting of much of the former with resultant appearance of very large raindrops at temperatures near 0°C .

When convection currents quickly transport great masses of these raindrops upward into the zone of below-freezing temperatures and snow, ice pellets or hailstones precipitate into the air carrying the large drops, instability often of great intensity is created by the processes previously outlined under X (a) and X (b). Violent upthrusts of the unstable, relatively warm, moisture-laden air ensue, with compensatory sinking of relatively cold air around the ascending columns. The flow of vapor and condensed forms of water substance into the portion of the thundercloud above the 0°C isotherm is greatly increased by these surges, with a resultant revitalization of the energy transformations occurring at higher levels, and an accelerated growth of solid hydrometeors.

In consequence of this, very heavy concentrations of intermingling solid and liquid hydrometeors are produced in zones where convergence of such hydrometeors occurs. An example of this may be found near the head of an ascending mass of buoyant, moisture-laden air when it collides with a descending mass of denser air lacking a sustaining convection current and bearing great quantities of ice pellets, hail, or snow. At the turbulent boundaries between adjoining currents moving relative to one another, there is likewise some exchange of entrained particles between them, with attendant growth of the frozen hydrometeors at the expense of the liquid ones.

As a rapidly ascending convection current passes above the level where its vertical upward acceleration is a maximum, its upward velocity continues to increase until it attains the level where, in general, the density of the air in the current becomes equal to that of the air in its immediate environment. The latter level is the height of zero upward acceleration of the current. Usually the current decelerates above this level, since then it is rising solely by virtue of its momentum while penetrating a stably stratified environment which offers restraint to upward intrusions.

The energy associated with the decelerating current under these conditions must be dissipated by extremely turbulent motions, especially those connected with overshooting and divergence of the stream above the equilibrium level succeeded by rapid subsidence.

Accordingly, the upper portion of an "air fountain" within a cumulo-nimbus cloud will invariably yield "rough air"; but if the ascending air transports considerable quantities of supercooled water which penetrate a layer containing myriads of ice particles, the resulting turbulence may become severe.

Zone of Maximum Vertical Exchange of Liquid and Solid Hydrometeors

From the foregoing considerations it is apparent that the instability-producing processes described under X (a) and X (b) lead to the development of quite effective mechanisms for accelerating the vertical transport of liquid hydrometeors upward through the 0° C isothermal surface, and of solid hydrometeors downward from the upper portion of the thunderstorm. It may be expected that there exists a stratum where both these effects tend to be a maximum, and it seems reasonable to believe that this stratum occupies the space from the level of the 0° C isothermal surface to the level of roughly the -4° C isothermal surface, extending also possibly in the other direction approximately to the level of the 4° C isotherm. In this layer the convergence of frozen and liquid hydrometeors will tend to be a maximum, with a resultant tendency for hailstones and ice pellets to attain their greatest rate of growth in the same region.

Possible Development of Horizontal Pressure Gradient and Vortical Motion

The marked lowering of the mean air density by the rapid liberation of latent heat in a column of appreciable depth lowers the barometric pressure at the base of the column compared to the surrounding atmosphere, and thereby produces an inward-directed horizontal pressure gradient. This tends to produce horizontal convergence around the periphery of the specified column; hence it acts to increase the concentration of hydrometeors and strengthen the vertical motions within the column. Prolonged continuation of such processes may produce a "necking-in" of the cloud and possibly some degree of horizontal circulation (i.e., vortical motion about a vertical axis).

Phenomenon of Buoyant Streaming of Air Past Frozen Hydrometeors

Relatively massive solid hydrometeors may congregate in the specified convergence layer for a time. But the assemblage may be rather concentrated only so long as the vertical upward current is sufficient in velocity under the given conditions to sustain the individual ice pellets, hailstones, or snow particles which are continually falling relative to the air enveloping them. Considerable latent heat is liberated in this region by sublimation and by freezing of water (as isolated droplets, collided droplets, or films of liquid on solid hydrometeors after the latter suffer impaction by droplets). The heat thus realized must render the enveloping air buoyant, and create an upward convective flow of the air¹ contiguous to the frozen hydrometeors. This action greatly helps to maintain the transport of water vapor and small droplets into the overlying cloud from the underlying strata.

Results of Depletion of Water Droplets

When the ice pellets, hailstones, and snow particles attain to considerable sizes and heavy concentrations, they tend to deplete rapidly the available intermingling water droplets by ice accretion and sublimation. This process reduces the vapor density in the space nearly to the equilibrium vapor density at the surface of the solid hydrometeors. Then the differential heating in the vertical column explained under X (a) and X (b) suffers a marked decrease. This causes a corresponding decrease in the vertical velocity of the ascending stream of air relative to the solid hydrometeors, since the latent heat for creating buoyancy of the air is no longer being released in such great quantities. Thus the limited system under consideration tends to attain a thermodynamical state of neutral stability.

By virtue of the changes described, the force of sustentation from the ascending current which enables the solid hydrometeors to remain in a given layer is largely removed, thus causing them to precipitate out. At first, the largest hailstones fall from the layer, and soon the moderately and perhaps smaller sized ones accompanied by ice pellets and snow follow.

Formation of Downdrafts

So great may be the aggregate mass of these hydrometeors falling into a given volume of air at temperatures above 0°C ,

¹Increased rate of vapor flow and heating from sublimation result.

that only a fraction of their bulk is immediately melted. The consequent removal of latent heat of fusion from the air in the relatively warm layer receiving the frozen hydrometeors cools that air relative to the underlying air stratum as previously explained. This steepens the lapse rate between the two cloud strata, and in general will produce instability for saturated air. As a result, descending currents are readily produced, so that the hydrometeors accelerate in their fall relative to the ground. Often by the time the heavy concentration of hailstones and accompanying precipitation has fallen the distance from its starting layer to the base of the cumulo-nimbus, it has attained a considerable velocity.

Of further importance is the fact that the cross-sectional areas and the terminal velocities of the hailstones and associated particles are much greater on the average in the given condition than those of ordinary cloud droplets. Accordingly, when the sustaining current fails, the larger hydrometeors with their greater terminal velocities exert a strong downward drag on the surrounding air and so produce a powerful descending current which, because of the instability, gains in momentum as it progresses.

After that current emerges from the cloud base, evaporation of the water both in the liquid and solid phase accompanied by some melting of the frozen precipitation occurs around the portion of the current exposed to the unsaturated air. The latent heat absorbed by this process cools the surrounding air and causes it to sink to lower levels.

Near the leading edge of the descending current, the moisture-laden air remains saturated and warms at the saturated adiabatic rate; while immediately beneath, the unsaturated air, which is driven downward ahead of the current, warms at the dry adiabatic rate. This steepens the lapse rate between the leading edge of the current and the underlying air, promoting the development of great instability for saturated air and permitting the downward acceleration of the current.¹ Prolonged continuance of this process allows the current to attain a high velocity and to undergo a great expansion in lateral extent. Severe downdrafts which are very hazardous to aircraft arise in this manner.

The downdraft and its contiguous sheath of air must be considerably cooler than their environment on reaching the surface, owing to the transport of hydrometeors and air from colder upper levels often under absolutely unstable conditions, the removal of heat by melting of the great mass of

¹Even with evaporation downward from the leading edge of current, absolute instability persists, if the air is convectively unstable.

frozen hydrometeors, and the removal of heat by evaporation. From these causes, which have contributed to the development of the phenomenon, there results a remarkable difference of density between the air within and without the downdraft. When the relatively dense downdraft, with its heavy load of torrential precipitation, strikes the ground, it must "splash" and produce cool lateral streamers or bodies of air flowing away from the area of impact. If the downdraft motion were perfectly vertical, the outflow would doubtless be initially radial and more or less symmetrical over level terrain; but if the motion were inclined relative to the ground, the outflow would probably be asymmetric with the greatest extension in the direction of the horizontal component of the current's original velocity on reaching the surface.

Lightning Hazards Near Column of Torrential Rain

Torrential rains which stem from the central regions of thunderstorms in the manner explained above are known (reference 12) to carry a large excess of positive electricity to the ground. In the region between the negatively charged cloud base and the heavy rain which is predominantly positively charged, the potential gradient becomes rather steep. On this account the specified region is one in which lightning strokes tend to occur frequently.

XI. PHENOMENA INVOLVED IN ELECTRICAL CHARGE

GENERATION AND SEPARATION

Important applications of the processes described above occur in regard to the generation and separation of electrical charges.

Charge Generation Effects of Collisions of Ice Particles

It is known that the collision of ice particles (or snow flakes) produces strong electrical charges, in general, such that the negative charges reside in the ice particles and the positive charges escape by means of small ions carried by the air. (See references 10, 11, 12.) When both large-scale and fine-grained turbulence are considerable, as when there is much intermingling of ice particles and water droplets in the layers previously mentioned, the particles

are jostled by collisions which occur with relatively great frequency and force.

Mechanism of Charge Separation

The liberation of latent heats of fusion and sublimation at the surfaces of the ice particles occurs at a comparatively high rate, owing (1) to the rapidity of ice accretion from frequent encounters with numerous water droplets, and (2) to the rapidity of frost deposition from the copious diffusion of vapor to the particles in the saturated atmosphere.

Under these conditions the continual evolution of heat at the surfaces of the particles (or hailstones) produces a steady streaming of air along the surfaces, directed upward as a result of the buoyancy induced by the thermal energy released thereon. Accordingly, positive ions which are formed by the collisions of ice particles are carried upward by the convective stream of air flowing in contact with the surfaces. Often two ice particles unite after a collision because of regelation at the point of impact and the freezing of water droplets which may be trapped between them. Relative to the air the larger resulting particle falls faster than the original parent particles did before the collision, and hence there is a comparatively rapid vertical separation of the positive ions and the negatively charged ice particles.

Hypothesis Regarding Charge Generation by Collision of an Ice Particle and a Water Drop

When a water drop collides at considerable speed with an ice particle, the former splashes and projects numerous minute fragments of water away from the site of the impact, while the remaining water spreads slightly on the surface and freezes. Considering the details of the phenomenon it seems quite possible that the electrical charges carried by the minute fragments are predominatingly positive even though the ice particles are largely negative, while the more massive calottelike deposit of ice formed from the residual water retains a predominantly negative charge. (This hypothesis should be tested. It should be noted in any case that the collision of ice particles is a more efficient charge-generation mechanism than the disruption of water droplets resulting from accelerations of the sustaining air current.) The minute projectiles of liquid water resulting from the splash are readily carried

upward by the general convective current which prevails, or at least are separated vertically from the ice particles by the greater terminal velocity of the latter.

Rate of Charge Separation

The progressive growth of the ice particles by ice or frost accretion tends to accelerate the separation of the bodies carrying the opposite electrical charges. In general, the positively charged ions will be conveyed by the convection current toward the upper portion of the cumulo-nimbus cloud where the ice crystals are largely concentrated (in the false cirrus structure), while the negatively charged ice particles will fall relative to the above-mentioned ions.

This conclusion is similar to that of Simpson. (See references 10, 11, 12.) It is to be emphasized that the mere falling of the originally minute ice crystals under the action of gravity as postulated by Simpson does not present a sufficient physical explanation of the speed of the separation of the oppositely charged carriers of electricity.

The rapidity with which electrical fields of intense potential gradients are built up within thunderclouds prior to lightning discharges (see reference 21) attests to the power and extent of the charge-generating and charge-separating mechanisms. Without the operation of processes whereby (1) the collisions between particles are caused to occur with great frequency and violence, and (2) the oppositely charged carriers of electricity are forced to separate at a rapid rate, the regenerative phase of the cycle of potential gradient variations in active thunderstorms would not manifest so much power as it actually does.

The greatest rate of charge generation would occur when one body of air containing a heavy concentration of large ice particles (or hailstones) and water droplets impinged squarely against another similar body approaching the first one at high velocity, so that numerous collisions of the particles occurred under exceedingly turbulent motions with high accelerations. Furthermore, the greatest rate of charge separation would occur (a) when the rate of evolution of latent heats of fusion and sublimation was a maximum, causing a swift upward convective current to transport the positive ions, and (b) when the rate of growth of the ice particles by various means as previously explained is a maximum, producing large hailstones which fall with greatest rapidity relative to the convective current.

It is to be expected on the basis of previously given considerations that conditions conducive to the evolution of these maximum rates of charge generation and separation are to be most commonly found in the neighborhood of a thin stratum (perhaps 800 to 1000 meters thick) approximately centering on the 0°C isotherm. (See sec. 6 for supporting evidence.)

Distribution of Charges in the Thundercloud

When the positive ions residing on the minute droplets or clusters of molecules arrive in the false-cirrus layer of the cumulo-nimbus cloud, they impart a positive charge thereto. On the other hand, when the ice particles fall into the lower portion of the cloud through the medium of the descending currents of air more or less surrounding the ascending central core of the active thunderstorm (see VIII of this appendix), they convey predominantly negative charges to the lower third of the cloud, especially toward the rear sector where descending motion is generally most widespread.

Acquirement of Positive Charges by Negatively Charged Rain

Falling from the Cloud

As a rule, negatively charged droplets precipitate out of the cloud as rain in a negative electrical field (i.e., one with a negative pole in the cloud base and a positive pole in the earth beneath). The droplets may acquire a net positive charge by capturing positive ions driven upward from the earth's surface under the action of the field, in accord with Wilson's theory. (See reference 22.)

Possible Cause of Positive Charge of Torrential Rain

It is of interest to consider now the result of the failure of an upward, convective current which sustains a relatively heavy aggregation of hailstones and other particles near the top of the fountainlike stream forming the core of the storm. The location of this concentration may be at high levels in the cloud, near the lower limit of the false-cirrus layer and therefore in a positively charged region. Consequently, the hailstones and other particles may acquire a net positive charge resulting from the flow of positive ions from below. Hence, when there occurs a slackening of the upward

velocity of the current so that it is insufficient to sustain the great quantity of frozen precipitation, the hail and associated particles rapidly descend under the unstable conditions which attend the phenomenon. En route, the hail and other frozen particles will melt partially or wholly before reaching the surface. It is to be expected that the precipitation will retain, at least in sign, its original predominant electrical charge and so arrive at the ground positively charged. This may be the explanation of why torrential rain originating from thunderstorms is strongly, predominantly charged with positive electricity.

APPENDIX VI

THEORY OF GENERATION AND SEPARATION OF ELECTRICAL CHARGES IN THUNDERCLOUDS

The theory of the causes of generation of electrical charges in thunder clouds and of their separation into regions where relatively high concentrations of charges of given sign may exist has not been worked out in all details to the satisfaction of the great majority of experts in the field. Therefore, no effort is made here to explain the matter fully. However, some pertinent facts and reasonable suppositions can be pointed out:

(a) The center of the upper, positively charged region is in every case at a temperature below $10^{\circ}\text{F} = -12^{\circ}\text{C}$. In view of the degree of coldness, most of the condensation in the cloud under these conditions is likely to be in the form of ice crystals, snowflakes, or other frozen precipitation.

(b) During blizzards in polar regions, which involve the blowing of large masses of snow, very strong electric fields are created at the earth's surface. These fields, with relatively few exceptions, are positive in direction - that is, the same as would be due to a concentration of positive charges above and negative charges below. This is the character of the electric field observed in the zone (Z_{PN})¹ between the upper, positively charged region of thunderclouds and the lower, negatively charged region. It seems quite certain that the generation of electric charges in this instance results from collisions of ice crystals, or snowflakes.

¹See sec. 17.

(c) Simpson (references 10, 11, 12) has suggested that the impact of ice crystals causes the ice to become negatively charged and the air positively charged. As he has pointed out, the settling of the negatively charged ice crystals relative to the positively charged air would, under this hypothesis, result in a separation of electricity with the positive charge above the negative. This explanation has not been confirmed by satisfactory laboratory experiments. However, there is abundant evidence that snow generally falls in a charged state. Also, the rather intense electric fields produced at the ground during snow storms, and the charges imparted to exposed objects by triboelectric action involving ice crystals or snow, as evidenced by precipitation static (see sec. 12), provides strong supporting evidence that frozen precipitation has characteristics adequate to yield, in the main, the observed distribution of charges in thunderclouds. It therefore appears probable that the phenomenon in question plays an important role in the generation of electricity in thunderstorms, and could possibly explain, at least in part, the separation of electrical charges so that positive charges will collect at the top of cumulo-nimbus clouds and negative charges will collect below, since such clouds always have ice crystals in their upper portion at least.

(d) Experiments have shown that when water droplets are violently disrupted by large acceleration or deceleration, the larger remaining droplets acquire positive electrical charges; whereas the smaller (often submicroscopic) droplets acquire a negative charge. Simpson has suggested that in the turbulent region of thunderstorms where rain collects in huge quantities sustained by vertically ascending currents, the droplet-splitting process can generate electrical charges and separate them. The droplets, lagging behind the ascending air currents, will be positively charged, while the currents will carry negative charges upward. As pointed out by Simpson, this could explain the (Q) region of lower, positive charges, and provide a mechanism whereby the (N) region of negative charges could acquire negative charges from the ascending air currents. (See diagram.)¹

(e) When ice crystals exist in a space side by side with water droplets at a temperature below 0° C, the ice crystals will grow at the expense of the droplets, for condensation will occur on the crystals and the droplets will evaporate. (The reason for this is that the saturation vapor pressure over ice is less than the saturation vapor pressure over water at the same temperature.) Ice crystals thus grown will fall faster than otherwise and so collide with water droplets at

¹See sec. 17.

lower levels. As long as the temperature is less than the freezing point ($32^{\circ}\text{F} = 0^{\circ}\text{C}$) the droplets are supercooled and will quickly freeze on impacting with ice crystals. The enlarged ice crystals will fall even faster than before, collide with more droplets, grow still more, and tend to continue in rapid descent unless caught up in a more rapidly ascending air current which may sustain them. (Hail forms by a succession of ascents and descents of an ice pellet in the supercooled water region of cumulo-nimbus clouds, whereby freezing and collection of more liquid occur alternatively.) When snowflakes or large ice crystals or pellets formed by the processes outlined above fall down through a cloud to a point below the $32^{\circ}\text{F} = 0^{\circ}\text{C}$ level, melting begins. When the melting is complete and evaporation is not excessive, falling raindrops are left. There are reasons for believing that the mechanism described above is necessary before rain can have moderate or heavy intensity. On the foregoing basis, the electrical charge acquired by a raindrop will depend, at least partly, upon the electrical charges possessed by the initial ice crystal and the water droplets or other ice crystals with which collision occurred, as well as upon the charges generated by collision of one ice crystal with another and by splitting of droplets. Heavy rain falling from the lower, positively charged (Q) region can be expected to be charged positively on the whole as shown by the diagram in section 17.

(f) If raindrops are carried up to the higher portion of the cloud by a strong ascending current some splitting is likely, whereby the remaining fragments will become positively charged and the progressing air current negatively. The air currents might convey the negative charges to the outer fringes of the cloud where descending currents often exist. The negative charges may thus be brought down to lower levels, while the positively charged fragments of rain may accumulate in the upper portion of the cloud, as suggested by Humphreys (Monthly Weather Review, vol. 67, Sept. 1939, p. 321). This would augment the electrification from other sources: positive in the upper portion of the cloud and negative below. Since the cumulo-nimbus cloud is exceedingly turbulent, it can reasonably be expected that the distribution will not always be perfectly regular and that at times the cloud will contain electrically charged regions which differ in number, location, quantity of charge, configuration, and so forth, from those portrayed in the generalized diagram.

(g) The electrification of thunderclouds is determined also to some extent by the action of air ions in the existing electrical field, according to a theory propounded by C. T. R. Wilson (references 22 to 24) and explained as follows:

Air ions (i.e., charged carriers of electricity) are always present in greater or lesser degree in the atmosphere. During fine weather there exists an electric field near the surface of the earth the intensity of which in terms of potential gradient averages about 100 volts per meter. This field has a "positive" potential gradient, by which is meant that it is a field such as is produced by a positive charge above and a negative charge below. Hence, in fine weather the earth has a negative charge relative to the air. Positive ions are therefore driven downward by the positive field and negative ions are driven upward.

Consider a cloud largely consisting of neutral droplets of water of different sizes. The larger droplets fall faster than the smaller droplets; hence there is a tendency for separation. In an ascending current the same tendency will prevail. Fog and small cloud droplets which are about 0.01 millimeter (about $1/2500$ in.) in diameter will fall at the rate about 0.003 meter per second (about $1/100$ ft per sec) relative to the air; light rain droplets which are about 0.45 millimeter (about 0.02 in.) in diameter will fall at the rate of about 2 meters per second (6.5 ft per sec); while excessive rain or shower droplets which are about 2.1 millimeters (about $1/10$ in.) or more in diameter will fall at the rate of 6 to 8 meters per second (20 to 26 ft per sec). Droplets greater than 5.5 millimeters (about $1/5$ in.) in diameter cannot remain at that size for they are split into smaller droplets on falling through the air. The large raindrops formed in cumulo-nimbus clouds by the process previously explained (see (e) above), will therefore probably fall at rates of 6 meters per second or more.

The ions driven by the existing potential gradient will have velocities less than the sinking speeds of these large raindrops, for with fields of potential gradient less than 40,000 volts per meter, both large and small ions will be moving at less than 6 meters per second, while with fields larger than this only the large ions will be effective and these will have similar low speeds. The order of magnitude of the difference in velocity can be seen from the fact that ordinary large ions will move through air with a speed of roughly a few hundredths of a meter per second in a field of 1,000,000 volts per meter.

The electrification process is described by Wilson for the more rapidly falling drops as follows:

"A neutral drop falling through the air in a field of positive potential gradient, at a speed greater than that with which the positive ions are being driven by the field, will attract and absorb negative ions at its lower positively charged surface; positive ions cannot reach its negatively charged upper surface from above as they cannot overtake the drop. It is only positive ions which the falling drop has overtaken (or in other words which have been carried up by the air from below the drop) that can approach its upper negatively charged surface; and these have all already suffered repulsion by the lower positive half of the drop before they come under the influence of the upper negatively charged half. The originally neutral falling drop will at first catch only negative ions; and in air of equal conductivity for ions of both signs, it will continue to catch more negative than positive electricity until a resultant negative charge is acquired amounting to a considerable fraction of the induced charge."

The process thus outlined will cause the larger drops which sink to lower levels to take on a net negative charge.

On the other hand, the much smaller cloud droplets held in suspension by the rising air currents on account of their low sinking speeds will tend to concentrate at levels above the larger droplets, and hence the positive ions descending in the existing field will be attracted to and absorbed by the upper, negatively charged portions of the small droplets. The very small droplets in the upper portion of the cloud will therefore acquire positive charges.

Thus a strong electric field may be established between the larger, negatively charged drops below and the smaller, positively charged droplets above. This field, like the fine weather field in the lower atmosphere is positive; hence the process of electrification described above can proceed until the potential gradient becomes so intense that breakdown of the field occurs by a lightning discharge, or the rate of leakage of charges between the two oppositely charged regions with resultant neutralization equals the rate of generation.

The theory outlined above seems capable of explaining the development of the lower, negatively charged regions and the upper, positively charged regions of thunder clouds, so far as the water droplets are involved. How well the process functions in the layers where ice crystals predominate is not known, but at any rate it is possible that it exerts a modifying influence tending to produce the observed distributions

of positive electrical charges at the higher levels and negative charges below.

The generation of charges in cumulus clouds which as a rule are entirely composed of water droplets may be presumed to depend on the processes already described as involving such particles.

The theory proposed by Wilson does not explain how a small region of positive charges can develop in the lower portion of thunderclouds, and for this the breaking-drop theory (of Simpson) outlined in paragraph (d) above must be invoked. However, the former theory can explain the falling of positively charged rain at the surface by a process which depends on the fact that below the negatively charged base region of thunderclouds the potential gradient is negative. In this process, the upper portions of the raindrops between negative cloud base and ground will have a positive charge induced, while the underneath portions will have a negative charge induced. Positive ions driven up by the negative field will be attracted to and absorbed by the descending drops which may thus acquire a net positive charge before they reach the ground. This helps to explain why more positively charged rain than negatively charged rain is observed at the ground. The charges accumulated in rain by any process may induce potential gradients strong enough to lead to a breakdown of the field, with resultant lightning discharge. Aircraft in the vicinity of such charged streams of rain may therefore suffer the passage of a discharge. (See reference 22.)

APPENDIX VII

THE NATURE OF LIGHTNING DISCHARGES

Lightning is essentially similar to a spark in nature and consists of a stream of electrical charges traveling at high velocity. Before there can be a lightning discharge it is necessary, first, that there be a region where a large concentration of charges exists; and secondly, that at some point near the region the potential gradient reach a magnitude which exceeds the critical sparking value (1,000,000 volts per meter at normal air density in the presence of large cloud droplets).

Generally, two regions of opposite charges are involved and the intensity of the potential gradient between them is

largely determined by the quantity of charges in the regions, their distribution, and the distance apart of the regions. The greater the quantities of electricity and the less the distance between them, the more intense will be the field.

Where the base of a thundercloud is strongly charged, say negatively, charges of opposite sign (here positive) are induced on the earth's surface beneath. Under these circumstances, a field with negative potential gradient is produced between cloud base and ground, where the effect of the much higher, positively charged region is not sufficiently great to overcome that of the lower negatively charged region. Under the influence of this field, positive ions are driven upward and negative ions are drawn downward.

The induced positive charges on the earth's surface tend to concentrate in areas of relatively high conductivity such as moist ground, streets with pipes, wiring, and so forth. When the potential gradient at the surface reaches a value of about 20,000 volts per meter, which is rare, point discharges (St. Elmo's fire) occur from sharply pointed objects, such as trees, spires, and so forth. The charges thus ejected into the lower atmosphere are carried up by the field and create a positive space charge beneath the cloud, provided the electrical conductivity just below the base of the cloud is appreciably less than that at lower levels. This space charge increases the potential gradient immediately below the negatively charged cloud base. It is thus possible for the potential gradient to reach abnormally high values locally in this zone, provided the neutralizing effect of the positive ions entering the negative cloud base is overcome by the replenishment of negative charges by electrical generation processes in the cloud. (See references 23 and 24.)

Where oppositely charged cloud or rain masses pass each other closely, the potential gradient between them becomes abnormally high. At any point where the value of the potential gradient reaches the critical sparking potential, a breakdown of the field, manifested by initiation of a discharge, will occur. If the point in question were in clear air at normal atmospheric pressure (29.92 in. of mercury) and density, the critical sparking potential necessary to attain this end is about 3,000,000 volts per meter, but since the critical sparking potential is proportional to density, it would be only about 2,100,000 volts per meter in clear air at a height of about 10,000 feet. When water droplets of 3 millimeters diameter exist, the critical sparking potential will be only about 1,000,000 volts per meter (reference 4).

Consider that at some point near a negatively charged cloud base the critical sparking potential has been attained; then a complicated discharge process takes place, depending upon the existing conditions of potential gradient and ionization in the atmosphere. The following description of the discharge process of lightning, largely based on the work of B. F. J. Schonland and his collaborators (reference 25), involves at least three stages or processes in the case of the typical single cloud-to-ground stroke: namely, (a) the pilot streamer, (b) the stepped leader, and (c) the return stroke. When the stroke is multiple, then there are also involved other stages: namely, (d) the dart streamer, and (e) the return stroke, similar to (c), which are repeated as many times as the lightning reoccurs. These components of the lightning stroke have also been observed by McEachron (reference 26) and his coworkers in the United States.

The Pilot Streamer

(a) The pilot streamer, which is the initial phase of the lightning discharge, is a stream of electrons (negative electrical charges). It starts at the cloud when the critical sparking potential is reached and advances into the clear air at a speed ranging from about 62 to 1240 miles per second. It will propagate itself as long as the field in the clear air has average potential gradients of about 270,000 volts per meter or more.¹ The current carried by the typical pilot streamer is relatively small, being of the order of a few amperes, and possibly as low as 0.1 ampere.

As the negative pilot streamer blazes its way, it must prepare the air ahead in order to secure continued progress. This it accomplishes by producing ionization immediately in advance of the streamer tip by one or the other, or both of two processes: namely, (1) ionization directly produced by

¹In many cases, apparently, this high average potential gradient may not exist along the entire path of the pilot streamer just prior to its coming into being. The stream of negative charges creates a strong potential gradient just ahead of its tip, which enables it to progress. The potential gradient becomes especially intense as the streamer nears the earth, for charges of positive sign are induced in the ground by the rushing away of electrons from neutral molecules in the area being approached, leaving the positive charges behind. The bringing of oppositely charged particles close together greatly strengthens the electric field, thereby facilitating the propagation of the streamer.

electrons in the tip of the streamer, and (2) photoionization. The latter is ionization of neutral air molecules by photons (i.e., bundles of light energy) emitted by air molecules excited to luminosity by electron impact.

In this manner, the pilot streamer may progress until it is close to the ground, provided the average potential gradients are sufficiently intense. The path followed by the pilot streamer is determined by the local variations in the potential gradient as it proceeds, and hence will be tortuous and branched (forked).

On account of the low current and low density of ionization in the pilot streamer relative to the current and density of ionization, respectively, in the subsequent stages of the discharge, the pilot streamer cannot be photographed with a fast camera but might be visible to the naked eye.¹ However, the pilot streamer leaves behind it for a very brief period of time a channel less than an inch in diameter characterized by considerable ionization.

The Stepped Leader

(b) The stepped-leader process cannot take place without this preliminary ionized channel prepared by the pilot streamer. After the pilot streamer has advanced a certain distance which varies from about 33 to 680 feet, a new stream of electrons, with a bright, luminous tip called a "leader," starts from the cloud down the channel with a speed of about 31,000 miles per second. This stream causes the channel to become luminous. When it overtakes the tip of the much slower pilot leader, it stops for an interval of time which ranges from about 31 to 91 millionths of a second. During this pause the pilot streamer has been advancing at the slower rate, but at the termination of the pause, another stream of electrons with a bright leader starts down the channel from the initial cloud point, approximately at the above-mentioned speed of about 31,000 miles per second, and again overtakes the tip of the pilot streamer. This steplike mode of progression is repeated again and again, possibly as many as 100 or more times until the earth is reached. In the process, the forward part of the stepped leader is propagated as a limited region of luminosity like an elongated fireball the length of which varies roughly from 80 to 370 feet (average about 180 ft).

¹See added note regarding pilot streamers at end of this appendix.

Each step carries the tip of the luminosity forward an average of about 160 feet along the ionized channel created by the pilot streamer. Hence, each bright step appears as the termination of a streamer of fainter luminosity extending the whole way down from the starting point of the discharge. As the end of a step is approached the streamer increases in brightness and decreases in width. Besides, every new, bright step generally starts a little way back on part of the track formed by the previous step, so that the portion of the step which is entirely new is about 90 percent of the whole.

Owing to the pauses, and despite the high speed of the stepped leader, the effective speed of the process is the same as the speed of the pilot streamer, which averages about 311 miles per second. The tortuous path taken by the pilot streamer is followed more or less by the stepped leader, so that a somewhat zigzag line, ordinarily with downward branches on the first stroke, represents the channel pursued. Forks in the pilot streamer channel produce the branches.

The current in the stepped leader, being higher than in the case of the pilot streamer on account of the lowered resistance offered by the ionized channel, carries down a considerable amount of negative charge in the form of electrons. These are first distributed throughout the step-leader channel and its branches, but decrease in number somewhat with time by combining with positive ions, by diffusion, and so forth. The atmosphere below the cloud thus acquires a channelized negative space charge as the stepped leader blazes its way to earth. The source of the charge is the charges in the negatively charged cloud particles in the lower portion of the cloud. In order for the latter to become available for the stepped-leader process, they must flow by progressive spark breakdown in the cloud surrounding the point at which the pilot streamer was initiated. This implies that cloud streamers, which form at lower breakdown potential gradients than streamers in virgin air, must feed the stepped leader by channelizing charges in the cloud and conveying them to the initial point in question.

The more extensive is the cloud space in which breakdown may be propagated from this point by the existing potential gradient and the greater the quantity of electrical charge which may thus be tapped from the cloud center, the greater will be the space charge lowered by the stepped-leader process. This tends to increase the potential gradient downward to the ground. Consequently, it is found that the streamers and their tips are generally much brighter in their later

stages when they are approaching the ground, than earlier, and moreover, this is accompanied by increase in effective velocity.

As the tip of the negative stepped leader gets very near the ground, it is probable that a positive streamer discharge occurs from the earth, where positive charges have been strongly induced locally. Upon meeting of the tip of the downward-moving, negatively charged stepped leader with the tip of the upward-moving, positively charged streamer from the earth, a continuous channel of highly ionized air thereby exists from cloud to ground, and a new stage of the lightning discharge sets in. This is called the "return stroke."

The Return Stroke

(c) The "return stroke" represents the intense flow of electrons from the ionized channel down to the earth, starting with the lower portion and progressing upward both along the main trunk and such branches as were formed during the stepped-leader process. Inasmuch as the ionization is of the greatest density in the lower portion, and the potential gradient is a maximum near the surface of the earth, the current represented by the rate of flow of charges has its greatest value at the surface. Consequently, the luminosity produced by the tremendous ionization and excitation of air molecules resulting from the current is of extremely great intensity. This is responsible for the intense flash of the return stroke, the tip of which moves upward along the channel with a speed ranging from about 12,400 miles per second to 87,000 miles per second. The most frequent speed is about 21,800 miles per second, although the speed is greater in the lower portion where the channel width and luminosity are greatest, and less as the return stroke progresses up the path where the channel width and luminosity are least.

When a return stroke passes an extensive branch blazed by the preceding leader, there is usually an appreciable decrease in channel width and luminosity of the return stroke above the branch, owing to the diminished source of charges to feed the upward-moving tip. Negative charges (electrons) thus drain out of the branches as well as of the main channel, whence the negative space charge below the cloud decreases to small values.

¹A fraction of the charges may be captured by raindrops or other precipitation particles which may thereby hamper dissipation of the space charge to some extent.

At first the current produced by the flow of these electrons to the upward-moving tip of the return stroke and thence down the channel to the ground increases with extreme rapidity. This rapid rise of current (called "steep wave front") occurs in a fraction of a millionth to several millionths of a second. Average rates of current rise in the wave front have been found to vary from about 1700 to 20,000 amperes per millionth of a second, and maximum rates have been found to range from about 4000 to 40,000, in the same units. The crest current in 50 percent of the return strokes exceeds about 23,000 amperes and may reach extreme values of 150,000 amperes or more. After the crest current is achieved, the current decreases at first rapidly and then more slowly until only about 1000 to 100 amperes are flowing. The wave of current here under consideration requires an elapsed time of about 10 to roughly 100 millionths of a second from the beginning of the stroke to the end of this phase.

Apparently this wave depletes the greater part of the electrons from the major and especially the lower portion of the channel and its connecting branches. In addition, the potential gradient between cloud and earth suffers a tremendous decrease after the crest current passes, but some gradient remains, at least near the cloud base. Thus, following the end of the current wave, there usually occurs a continuous, fairly steady flow of current of approximately 100 to a few thousand amperes, lasting for an interval of about 1/1000 to 1/10 of a second or longer. It can be expected that this continuing-current depends on the remaining low potential gradient and involves charges brought down to ground from the more remote portions of the channel and the cloud center originally tapped. There is also reason to believe that the currents in the return stroke at the higher levels of the channel are less than at the lower levels, nearer the ground.

The total amount of electrical charge carried in a lightning stroke may range from a fraction of a coulomb to about 300 coulombs. The average of the charge carried by a lightning stroke is in the neighborhood of 20 to 35 coulombs.

Effects of Component Parts of Return Stroke

Of great importance is the distinction between the effects of the different portions of the return stroke:

First, the steep wave-front, high-current, short-time stage produces explosive effects on account of the high rate

of liberation of energy from the intense electrical power of the stroke. Explosive effects may be manifested by violent expansion waves, sharp thunder, good-size holes punched in sheet metal which is in the path of the stroke, sudden vaporization of thin wires through which the current passes, and so forth.

Second, the continuous, low-current, long-time stage produces burning effects on account of the great amount of heat liberated in the long period of current flow despite the relatively low value of the current. Burning effects from this source are indicated by the small holes burned in the aircraft outer skin, and the pit marks fused on the skin, rivet heads, and so forth. An airplane traveling through or by a long-time, low-current stroke will show a number of such burns and pit marks along the outer structure in a rough line running opposite to the direction of relative motion of the two. Not much hazard can ordinarily result from passage through such strokes.

Many lightning strokes are multiple in nature, that is, repeat a cycle involving leader stroke to ground and return stroke. The leader stroke in such repeating discharges is called a "dart leader."

The Dart Leader

(d) The "dart leader" is a stream of electrons exhibiting a luminous, dartlike tip which travels down the channel ionized by the preceding strokes. It does not occur until a brief lapse of time following the previous return stroke. This interval varies from about 0.001 to 0.53 second. Unlike the leader in the initial stroke, the dart leader is not ordinarily stepped, but usually advances continuously down the channel from cloud to ground with a speed ranging from 620 to 14,300 miles per second. The most frequent speed is about 1240 miles per second. Sometimes, when an unusually long interval has elapsed between the preceding return stroke and the dart leader, the lower end of the usual dart leader becomes stepped like the leader to a first stroke. Dart leaders do not ordinarily branch like stepped leaders. Apparently, they tap charged cloud centers more or less remote from the cloud center discharged by the initial stroke. Consequently, it sometimes happens that more charges are transported by succeeding strokes than by the first one. When the dart leader reaches the surface, a return stroke occurs.

The Return Stroke in Multiple Strokes

(e) The return stroke which succeeds a dart leader has characteristics similar to those of the initial return stroke.

As many as 40 separate strokes have been observed in a multiple stroke. The maximum total time interval observed for a multiple stroke has been about 1.53 seconds.

Cloud-to-Air and Cloud-to-Cloud Strokes

Lightning discharges from cloud to air have been observed a number of times. In these cases the ground has not been involved, but the stroke has exhibited either the stepped-leader or dart-leader process without a return stroke. Presumably, here a strong potential gradient between a charged cloud center and a space charge of opposite sign was instrumental in initiating the discharge.

Lightning discharges from cloud to cloud or within clouds, involve the breakdown of the field between the oppositely charged centers of clouds or precipitation which come adjacent to one another. Observations have shown that there are many more of such discharges than of cloud-to-ground discharges. In many cases the breakdown is not explosive enough to produce thunder audible at the ground. From the facts at hand it appears probable that a number¹ of the instances of electrical discharges to aircraft have involved this gradually sloped, wave-front type of discharge, with a relatively low current peak, but fairly long duration.

Added Note Regarding Pilot Streamers

In laboratory observations of the development of electric sparks in air between metallic electrodes, there has been noted by some investigators, particularly Dunnington (reference 27), Slepian and Torok (reference 28), and Torok and Fielder (reference 29), a faint, hazy filament which rapidly traverses the space from negative pole (cathode) to positive pole (anode) immediately preceding the passage of the bright channel that represents the main spark breakdown.

¹It is quite possible if not probable that a majority of the disruptive discharges experienced have been of this character rather than of the steep, wave-front type.

It is possible that the initial hazy streak observed in the laboratory spark corresponds in character and function to the lightning pilot streamer which has been postulated by Schonland (reference 25, Proc. Roy. Soc., ser. A, vol. 164, 1938, p. 132) to be present in cloud-to-ground strokes, although never actually observed. However, it should be noted that the theories proposed by Schonland (reference 25), Meek (reference 30), Loeb (reference 14), and Loeb and Meek (reference 31) regarding the pilot streamer have been recently questioned on various grounds by Flowers (reference 32).

Presumably, the mechanisms of the various types of streamers manifested by the lightning stroke are profoundly influenced, firstly, by the characteristics of the thunderstorm which must act jointly in the roles of electrostatic generator and capacitor, and secondly, by the nature of the electrical circuit wherein there must be an electrical breakdown between cloud particles simultaneously with the confluence of charges from an assemblage of widely distributed charged water droplets, and crystals together with ions.

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Figure 1.- Burns on leading edge of propeller blade, near the top, due to a lightning discharge.

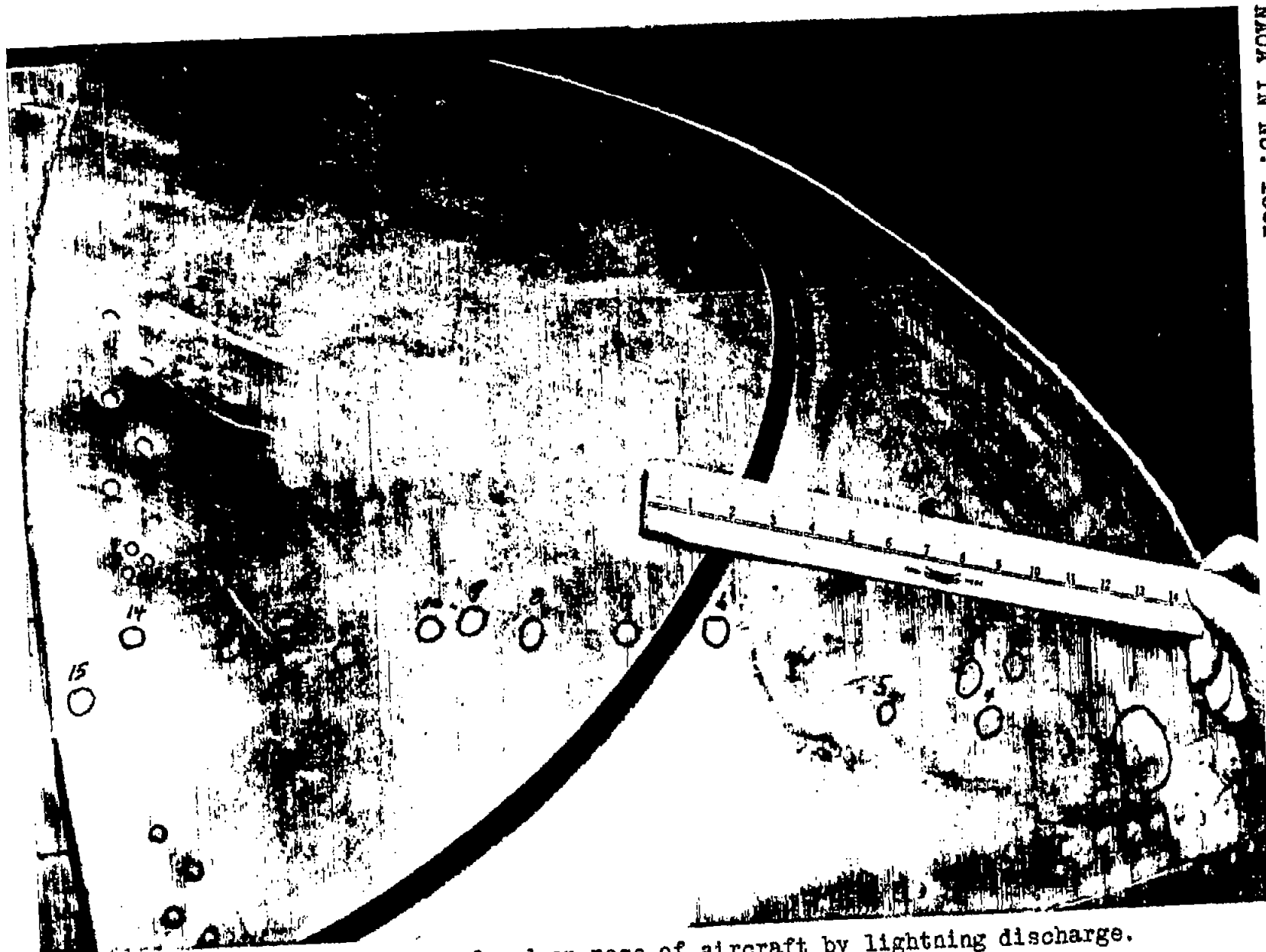


FIG. 2

Figure 2.- Fifteen spots fused on nose of aircraft by lightning discharge.

**LIGHTNING STRIKE
PLANE 068
RIGHT AILERON
3-27-41**

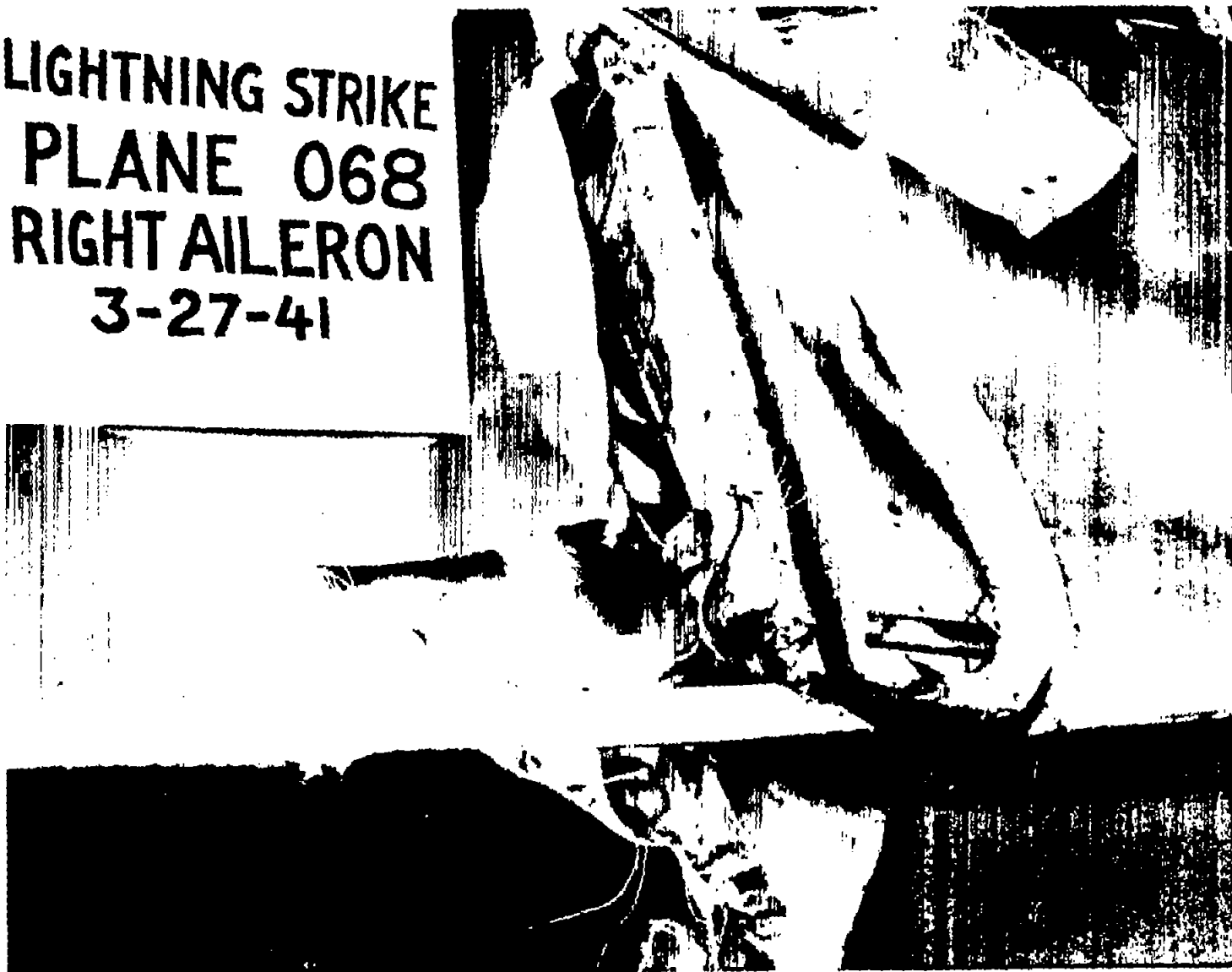


Figure 3.- Trailing edge former tube of right aileron severed by lightning discharge.
(Fabric removed to show extent of damage.)

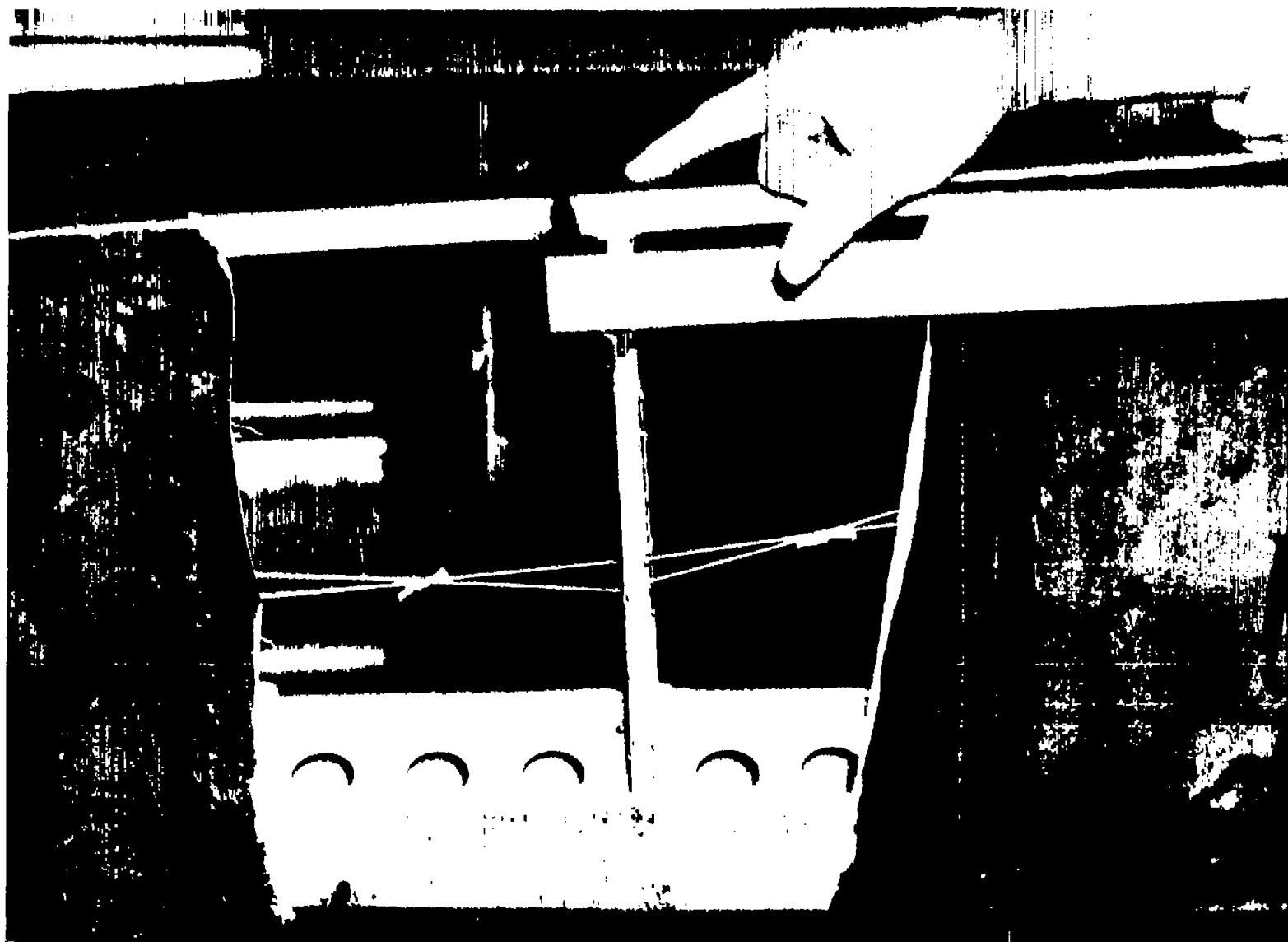


Fig. 4

Figure 4.- Burn to trailing edge of right aileron caused by lightning discharge.
(Fabric removed to show extent of damage.)



Figure 5.- Two holes burned by lightning in right wing trailing edge.



Figure 10.- Rupture of tail cone by lightning discharge.
All rivets were missing for a distance of approximately 24-inches forward from the tail light. The tail light was found hanging by its wires.

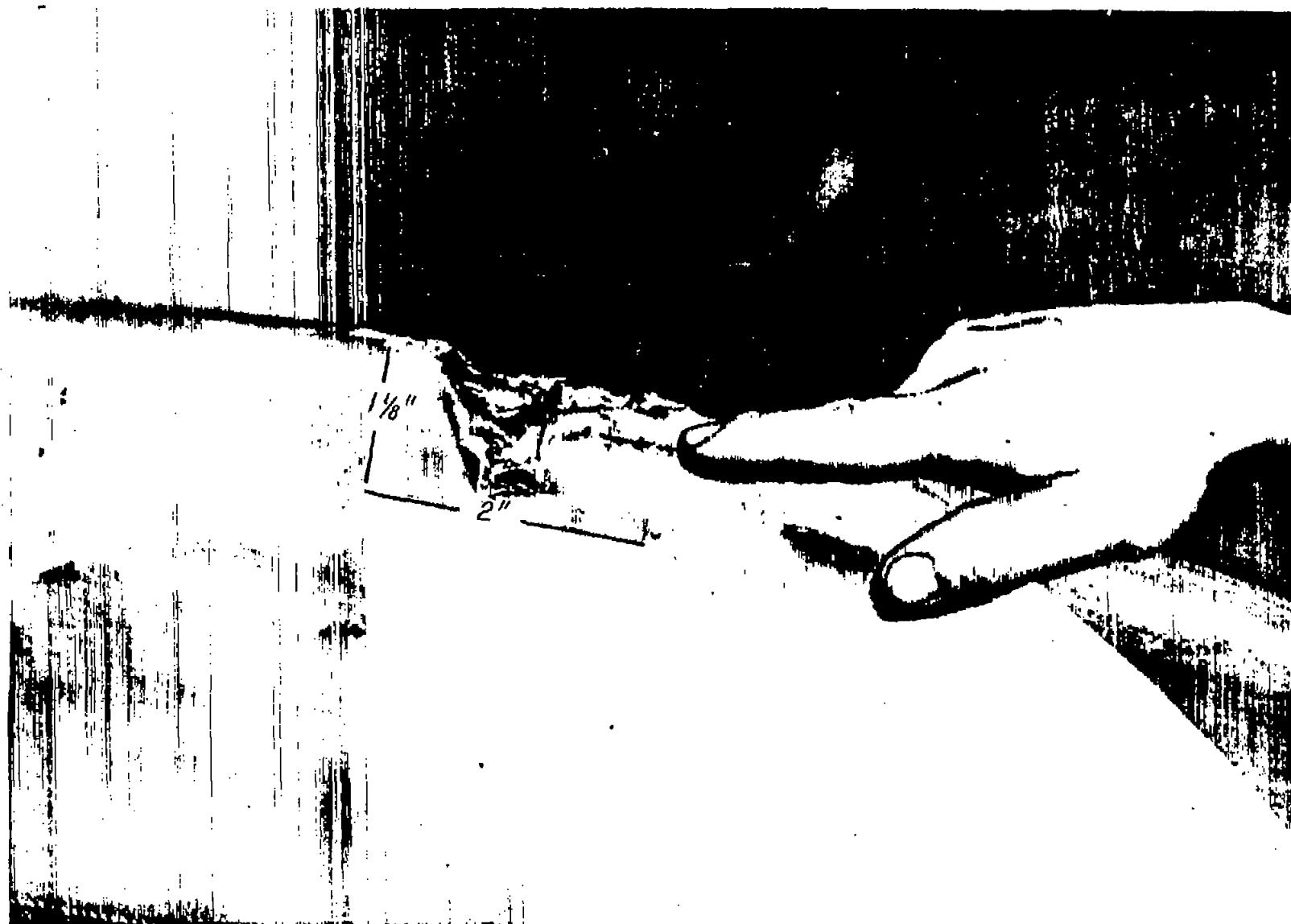


Fig. 6

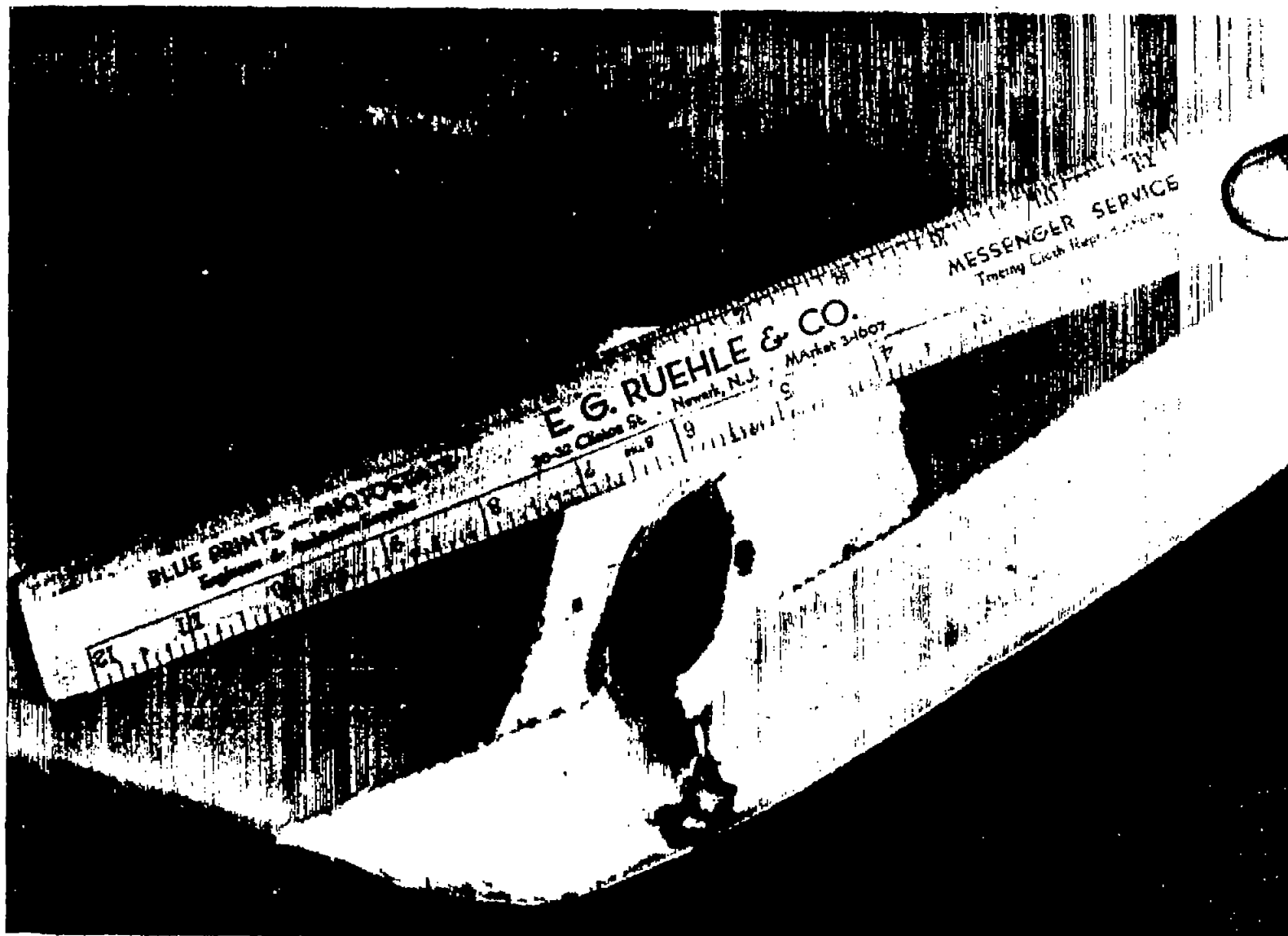
Figure 6.- Hole one inch in diameter burned by lightning in steel tubing at top of rudder.



Figure 7.- Holes burned through trailing edge former of right elevator and one spot burned through fabric by lightning discharge.



Figure 8.- Hole burned by lightning in trailing edge of right elevator. (Fabric removed to show extent of damage.)



NACA TN No. 1001

FIG. 9

Figure 9.- Hole burned in trailing edge of right elevator by lightning discharge.

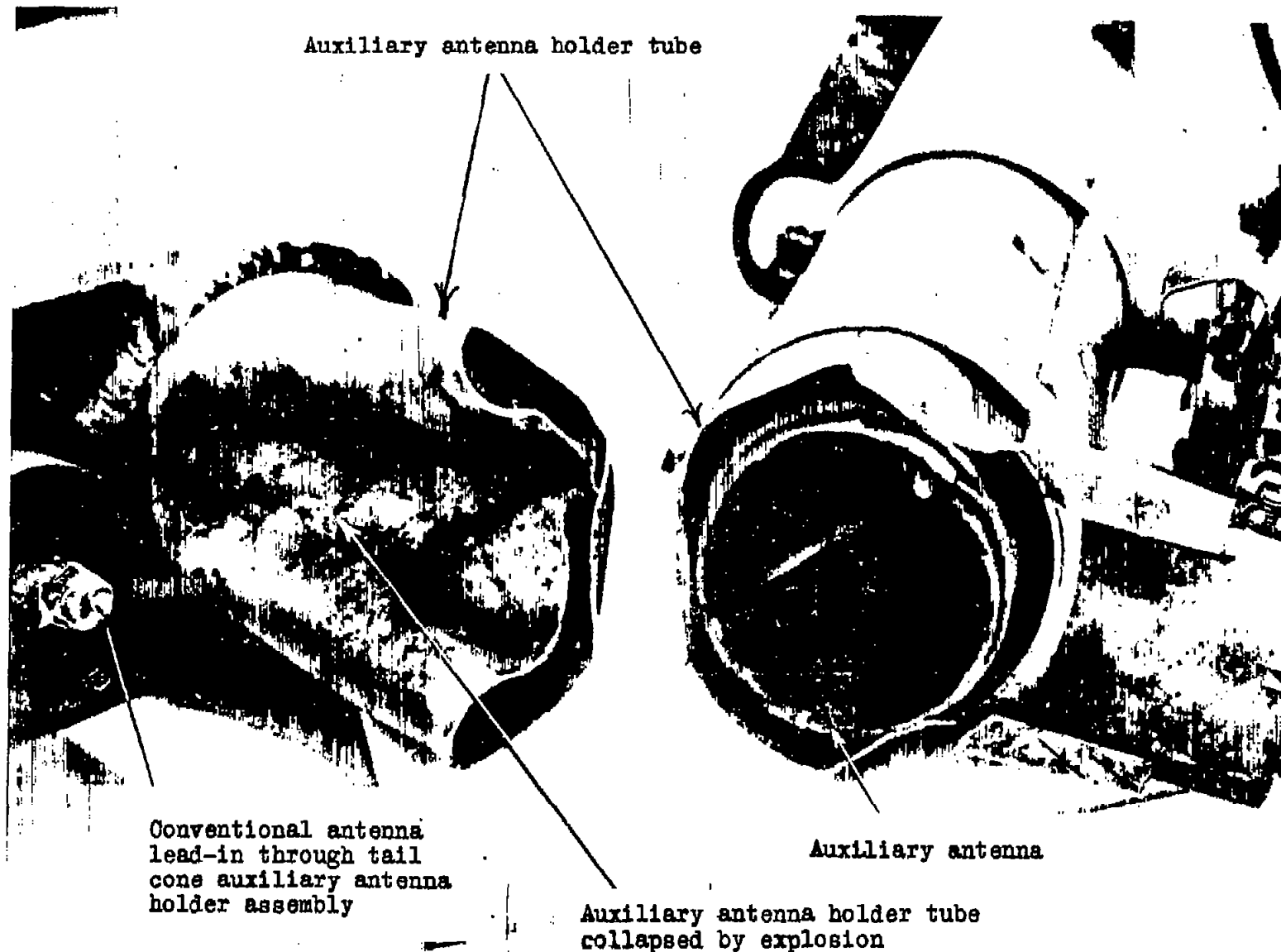


Figure 11.- Damage to an auxiliary antenna holder tube caused by a lightning discharge.

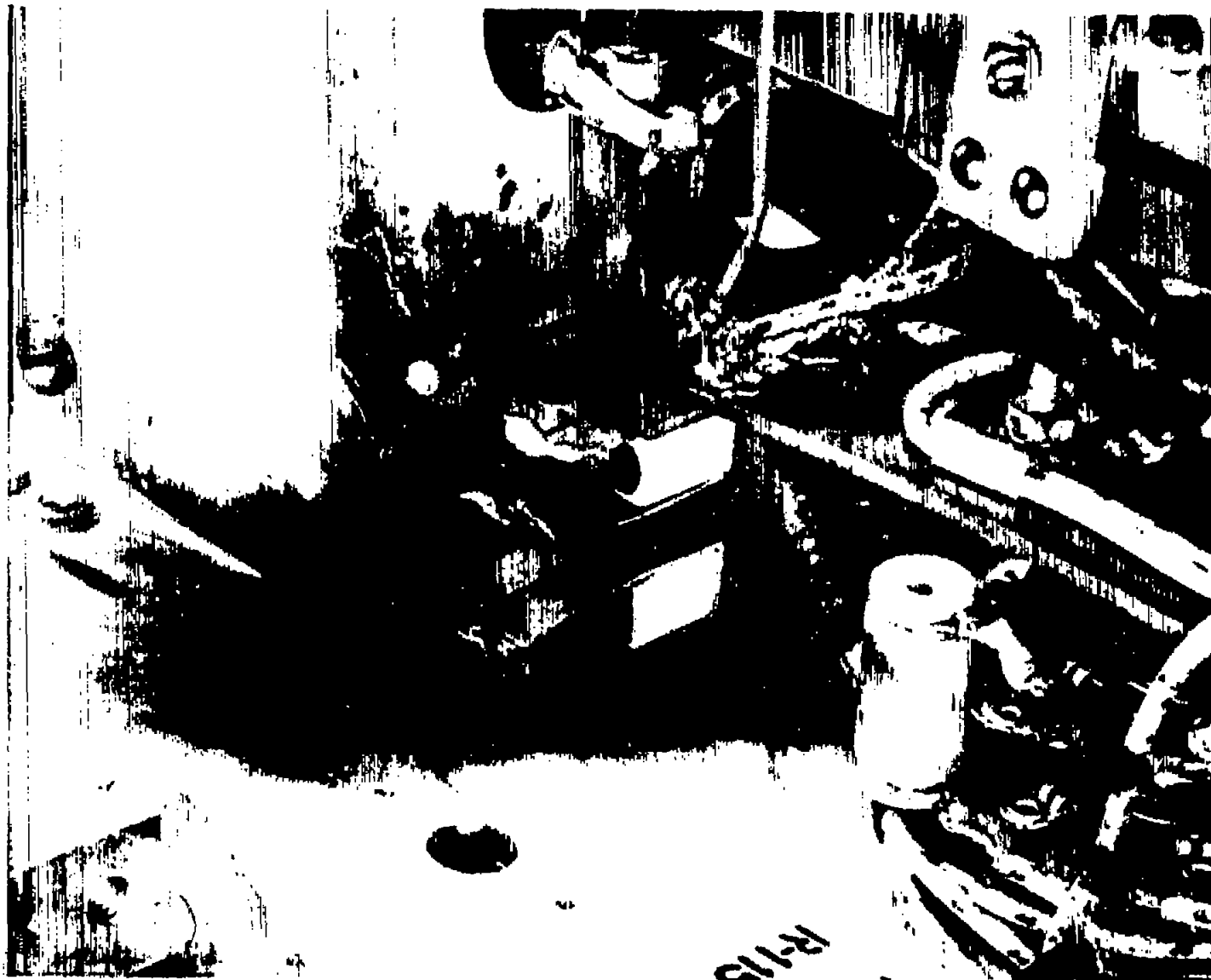


Figure 12.- Radio damage caused by lightning discharge to aircraft.

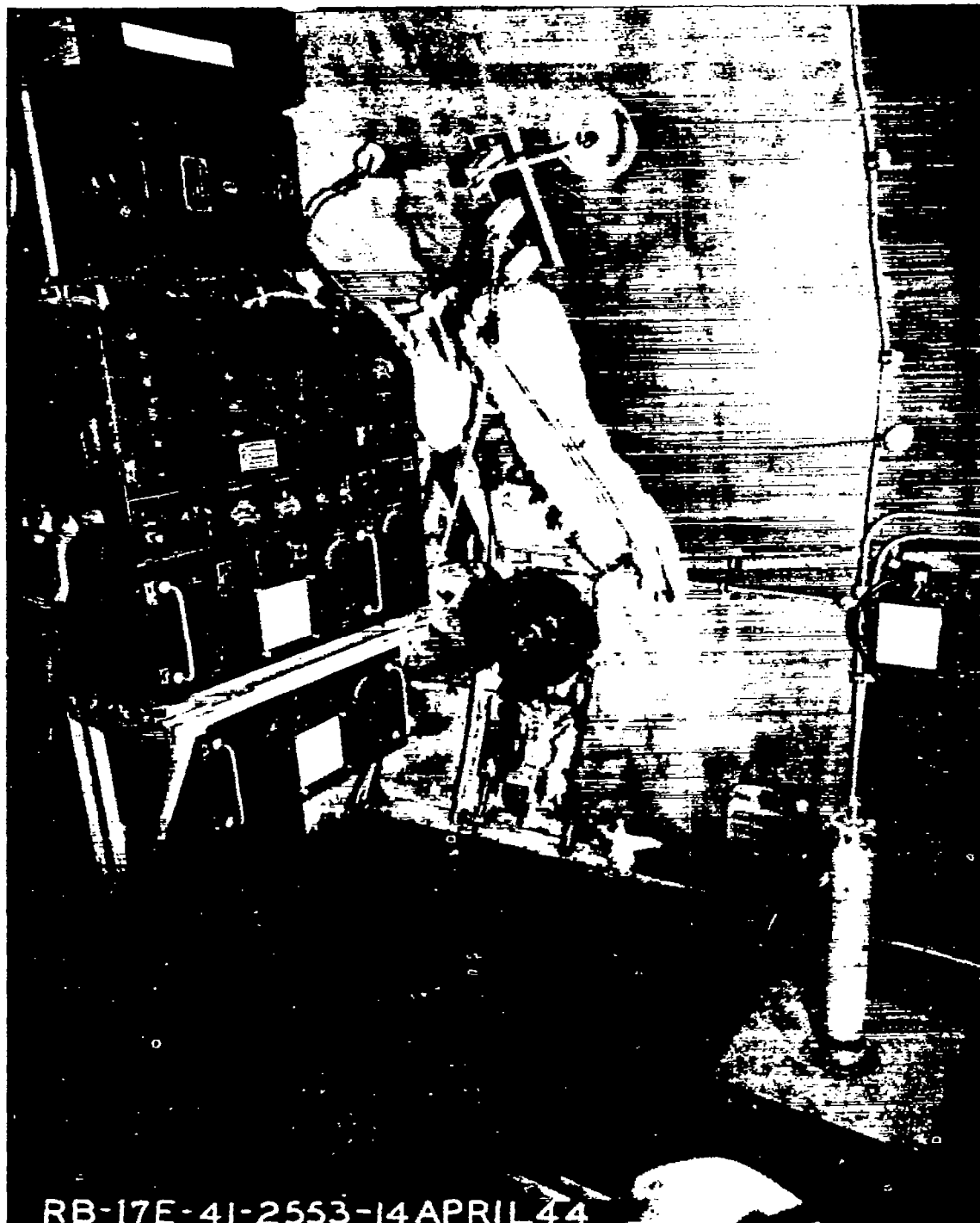


Figure 13.- Upholstery, lagging, and wiring burned on left side of fuselage immediately adjacent to trailing antenna reel by lightning discharge. Radio damaged.